Climate induced environmental changes during the Vistulian Lateglacial at Zabinko, Poland.

Bohncke, S.J.P.; Kasse, C.; Vandenberghe, Jef

published in
Quaestiones Geographicae
1995

document version
Peer reviewed version

CLIMATE INDUCED ENVIRONMENTAL CHANGES DURING THE VISTULIAN LATEGLACIAL AT ŻABINKO, POLAND

S. BOHNCKE, C. KASSE AND J. VANDENBERGHE

Vrije Universiteit, Faculty of Earth Sciences, Amsterdam, Netherlands

Manuscript received 22nd February 1995
Revised version 26th June 1995

Bohncke S., Kasse C., Vandenberghe J., 1995. Climate induced environmental changes during the Vistulian Lateglacial at Żabinko, Poland. *Quaestiones Geographicae*, Special Issue 4, Adam Mickiewicz University Press, Poznań, 1995 pp. 43-64, Figs. 14, Table 1. ISBN 83-232-0685-6. ISSN 0137-477X.

ABSTRACT. The sandpit at Żabinko contains a variety of stacked fluvial and aeolian deposits of Vistulian Late Pleniglacial and Lateglacial age. In combination with the lacustrine infill of a palaeo river channel, running northeast of the sand pit, these sediments offer the opportunity to study in detail the interaction between fluvial and aeolian processes in response to changing climatic conditions during the Lateglacial.

Braided river sediments at the base of the sand pit characterize the fluvial system that was active on the Late Pleniglacial/early Lateglacial bifurcation terrace of the Warta river. An abandoned branch of this system was subsequently filled with organogenic sediments of Bølling age and has its lateral equivalent in a palaeosol. These sediments and the soil are capped by parabolic dune deposits.

River adjustment prior to ca. 12.6 ka BP led to the abandonment of the braided system and an incising transitional system developed. At the site of Żabinko the transitional system was active up to the end of the Bølling, ca. 12.2 ka BP. At that moment the migrating inland dunes dammed the drainage through this channel. A subsequent further organization of the drainage pattern led to a second phase of river adjustment resulting in a meandering system. That system could still reach the former floodplain of the bifurcation terrace during periods of peak discharge and fine suspension load was deposited in the lacustrine sediments of the abandoned channel at Żabinko.

These lacustrine sediments, that accumulated in the abandoned branch of the transitional system, recorded the palaeoenvironmental evolution from ca. 12.2 ka BP. Within this river branch aeolian sands interfinger with lacustrine sediments and offer a refined tool to trace and date the phases of aeolian activity that led to the formation of parabolic inland dunes. Distinct maxima in aeolian activity follow dry conditions towards the end of the Allerød, ca. 11.2 ka BP, and the later part of the Younger Dryas between ca. 10.4 ka and 10 ka BP.

S. Bohncke, C. Kasse, J. Vandenberghe – Faculty of Earth Sciences, Department of Quaternary Geology, Vrije Universiteit, de Boelelaan 1085, 1081 HV Amsterdam, The Netherlands.

Introduction

The study area is situated in the Warta valley in the Great Polish Lowland of western Poland, ca. 30 km south of Poznań (Fig. 1). This region is classical for its climate-related Vistulian (Weichselian) Lateglacial, fluvial changes which are clearly expressed in the landscape morphology (Kozarski, Rotnicki 1977; Kozarski 1983; Gonera, Kozarski 1987; Kozarski et al. 1988 and Kozarski 1991). The exposure at Żabinko, dealt with in this paper, has previously been described by Kozarski, Tobolski (1981 p. 24-25), Nowaczyk (1986 p. 52-62), Kozarski et al. (1988 p. 191-192), Tobolski (1988) and Lemdahl (1991). The latter two investigated respectively the palaeoecology and insect remains of this site.

During the last glacial maximum the study area was located within the limits of the Weichselian ice sheet. The ice-marginal zone of the Leszno Phase (Fig. 2) in the south represents the maximum extent of the ice sheet. It was dated at ca. 20 ka BP (Kozarski, Tobolski 1981). The ice-marginal zone of the Poznań Phase, north of Poznań, was formed during a pause of the generally retreating ice front (ca. 18.4 ka BP). In between the glacial landforms of the Leszno and Poznań Phases the Warsaw-Berlin pradolina is found which functioned as an east-west melt-water drainage system during the Poznań Phase. Shortly after the Poznań Phase the Warta river breached through the glacial landforms of the Poznań Phase and the river developed a new northern course along Poznań (Fig. 2). At this stage the water bifurcated in two directions, partly continuing along the east-west directed pradolina, partly following the northern route through the newly formed gap (Kozarski

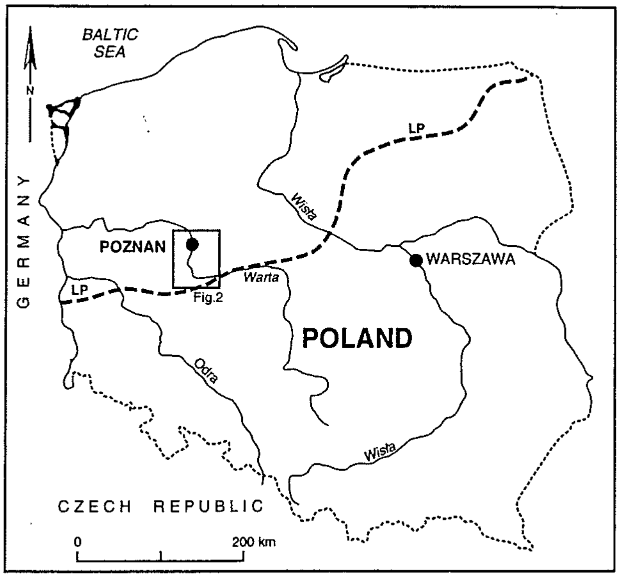


Fig. 1. Location map of the study area (rectangle) in Poland. LP (Leszno Phase) indicates the maximum extent of the ice sheet during the Vistulian (Weichselian)

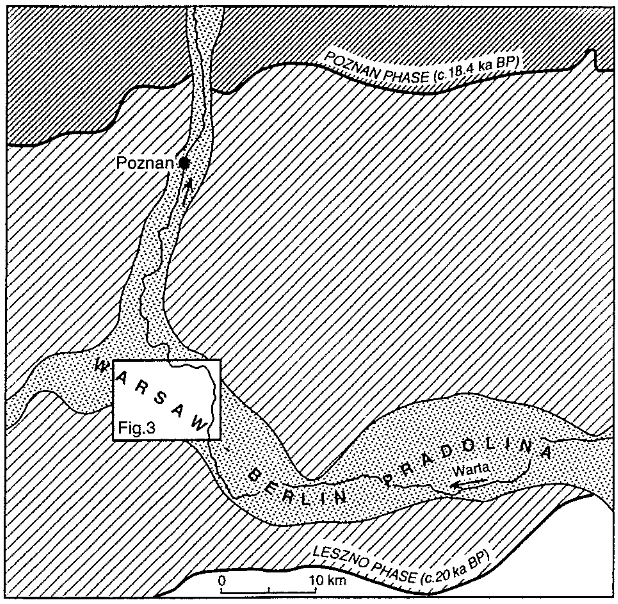


Fig. 2. Location of the study area and its relation to the ice-marginal zones of the Leszno and Poznań Phases and the Warsaw-Berlin pradolina

1983). The site of Żabinko is located at this bifurcation point (Fig. 2) and the oldest fluvial sediments in the investigated sites are part of this bifurcating system (Fig. 3).

In cooperation with the Adam Mickiewicz University of Poznań the fluvial and aeolian developments of the Warta river valley have been investigated and compared with the palaeogeomorphological evolution of the Maas river in the Netherlands for the Lateglacial period (Kasse et al. 1994; Vandenberghe et al. 1994). The latter study largely confirmed the general outline of the Warta Lateglacial evolution presented previously by Kozarski and coauthors: the Pleniglacial braided river was succeeded by a Lateglacial system with large meanders and by a Holocene system of small meanders. In addition a transitional phase, positioned in the Bølling period, could be established between the Pleniglacial braiding phase and the Lateglacial meandering phase. The transition to the Lateglacial large meandering system appeared to occur early in the Allerød period, instead of the Bølling as was previously stated by Kozarski, and persisted during the Younger Dryas period. The existence of large meanders during the Younger Dryas, is in strong contrast with the channel pattern of the Maas river, where a sudden adjustment occurred from large-scale meandering into braiding at the start of the Younger Dryas. This contrast has been explained by differences in grain-size and gradient of the two rivers (Vandenberghe 1994).

Apart from climate-related adjustment phases in the fluvial system, changes in the aeolian environment and changes in the intensity of aeolian deposition have also been reported previously for the study area (Nowaczyk 1986, p. 52-62; Kozarski, Tobolski (eds.) 1981; Tobolski 1988). According to these studies aeolian deposition increased on the braidplain at the end of the Pleniglacial. A second phase of major aeolian activity was established for the Older Dryas when parts of the late Pleniglacial braidplain were deflated and large parabolic dune complexes developed by WNW winds. From the fact that lacustrine silts, peats and soils of Bølling age have been found at the base of the inland dunes at Żabinko, it has been concluded that the land surface was rather stable during that period (Nowaczyk 1986; Tobolski 1988; Lemdahl 1991). These two aeolian phases correlate well with the major phases of aeolian activity defined elsewhere in Poland (Nowaczyk 1986; Manikowska 1977, 1985; Kozarski, Nowaczyk 1991). Aeolian deposition during the Younger Dryas has not been reported by the authors for the Żabinko area, although it has been reported from other sites in Poland (e.g. Manikowska 1985)

The aim of the present study is to:

i. reconstruct the depositional environments during the Pleniglacial and Lateglacial,

ii. establish the environmental conditions that induced river adjustment phases, especially from the Pleniglacial braided phase into the Lateglacial meandering phase,

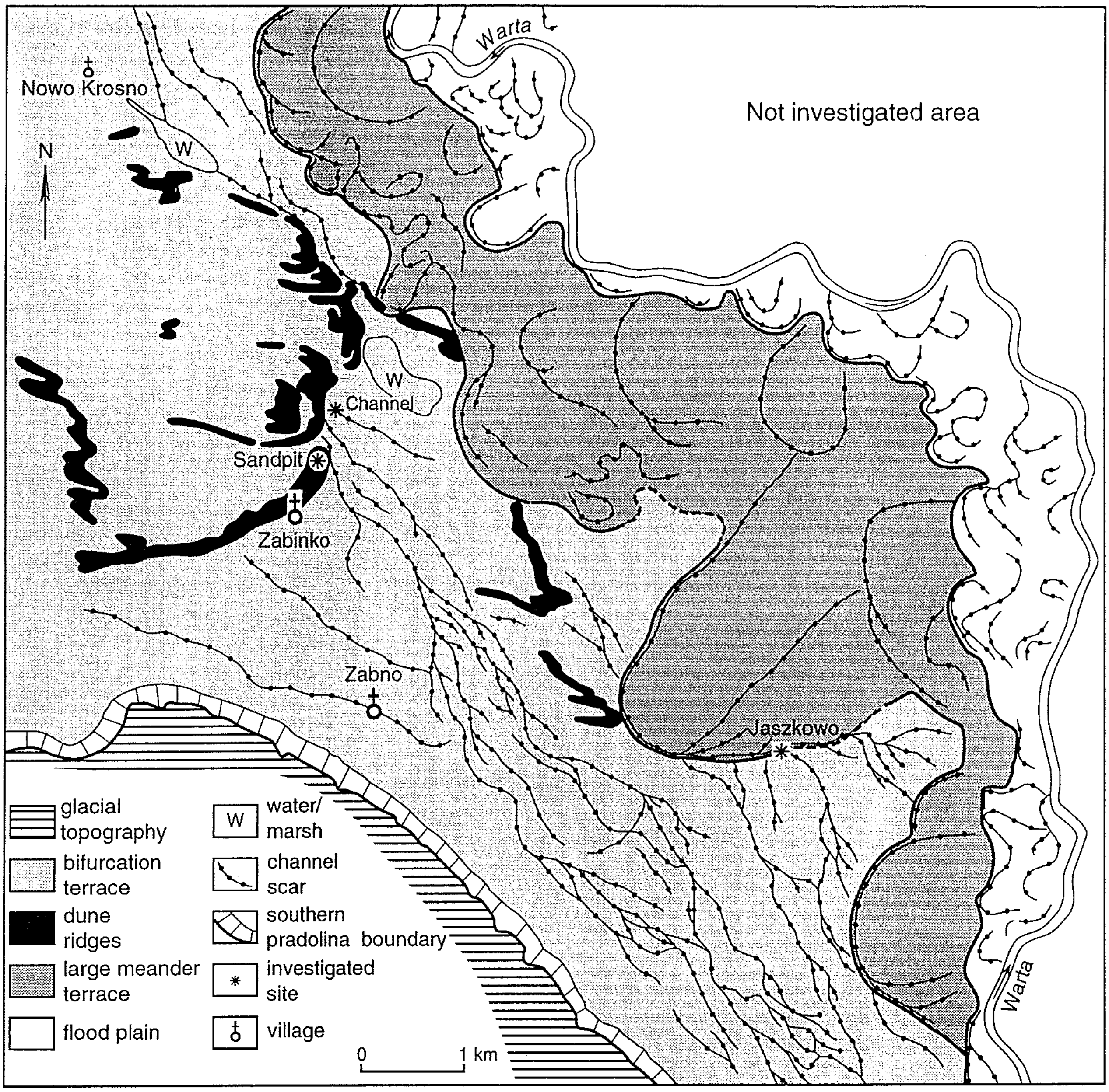


Fig. 3. Geomorphological map of the investigated area with the position of the Late Pleniglacial bifurcation terrace, Lateglacial large meander terrace and Holocene floodplain and their channel scar morphology

iii. identify and date phases of increased aeolian deposition and phases of stability.

With respect to the last point it is important to ensure whether the aeolian activity at Żabinko is restricted to the Older Dryas only.

The combined results of a sedimentological study in the Żabinko sand pit and palaeobotanical, loss on ignition and grain-size analyses of the infill of a palaeochannel of the transitional system, located at the lee side of a parabolic dune complex (Fig. 3), are expected to provide insights in the complex interaction between climate, vegetation, fluvial behaviour and aeolian activity.

Vistulian Late Pleniglacial and Lateglacial sedimentary environments at Żabinko

In the large exposure at Żabinko, situated on the bifurcation terrace (Figs. 3 and 4), four lithologic units are distinguished. The lower two units comprise the top of the bifurcation terrace of pre-Bølling age and are predominantly of fluvial origin. Unit III is a soil grading into a lacustrine deposit of Bølling age. Unit IV of post-Bølling age is largely an aeolian deposit which is part of a large parabolic dune complex overlying the fluvial sediments of the bifurcation terrace (see Fig. 3).

Sedimentological description and interpretation of the units

Unit I

Unit I is situated at the base of the sand pit at ca. 60-61 m a.s.l. (Fig. 4). It is dominated by medium to coarse gravelly sand with large-scale planar and trough cross-bedding (Fig. 4; Figs. 5 and 6 lower part of lacquer peels). The grain-size distribution of these sediments (Fig. 9: samples 1-2) shows a clear bimodality. The dominating population is medium sand (1.35 à 1.4ϕ) while the modal size of the minor component is about 2.7ϕ. The skewness of the sediment is relatively high (.55 to .82ϕ). Material <32 μm is virtually lacking. These grain-size characteristics indicate that the bulk of the sediment was deposited as bedload, while the finer component was deposited from suspension load. The sedimentary structures point to lower flow regime conditions and sediment transport and deposition by transverse bars and sinuous crested megaripples in the channel. The stacked character of the cross-bedded sets indicates rapid aggradation of the floodplain. The bedding types and vertical sequence resemble the South Saskatchewan type braided river system as described by Miall (1978). The current flow, derived from the planar cross-bedded sets, was dominant to the northwest. This direction is in agreement with the southeast-northwest oriented channel scars and interchannel bars on the bifurcation terrace southeast of the Żabinko exposure (see Fig. 3). The presence of frost cracks points to temporary exposure of the sediment surface. Their truncated nature and initial development illustrate the dynamic character of this braided environment. Moreover, these frost cracks point to (at least) deep seasonal frost conditions.

The age of the braided river deposits can be deduced by 14C-dating, from its geomorphological position and from the age of the ice-marginal zones. A 14C-date of 33,700 ± 2300 BP (GrN 16177, table 1) on an eroded peat clast (Fig. 4) indicates that the fluvial sediments are younger than 33 ka. The Żabinko site is located within the limit of the maximal

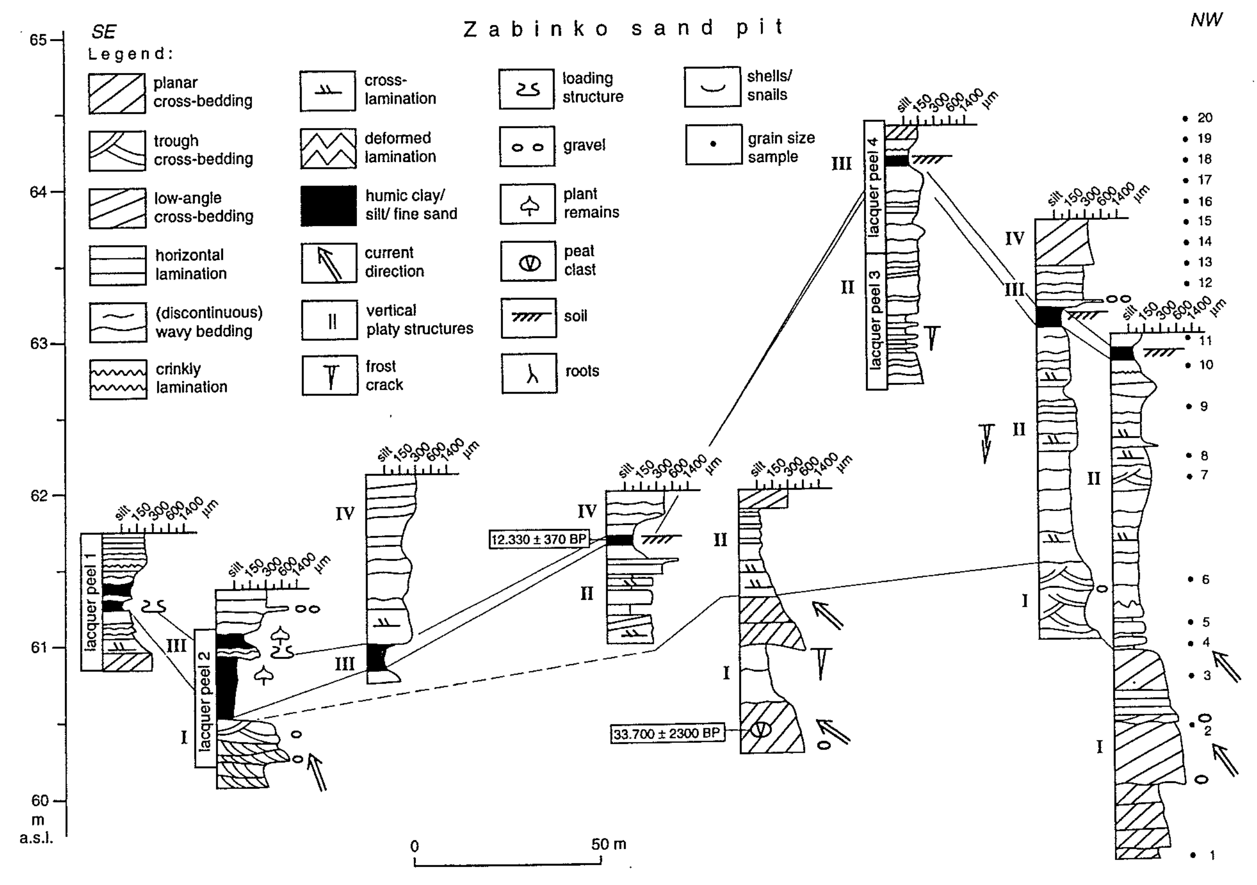


Fig. 4. Sedimentary logs of sand pit Żabinko (location in Fig. 3). Unit I and II are Late Pleniglacial braided river sediments. Unit III is a Bølling age soil or lacustrine deposit. Unit IV is the base of a Lateglacial dune

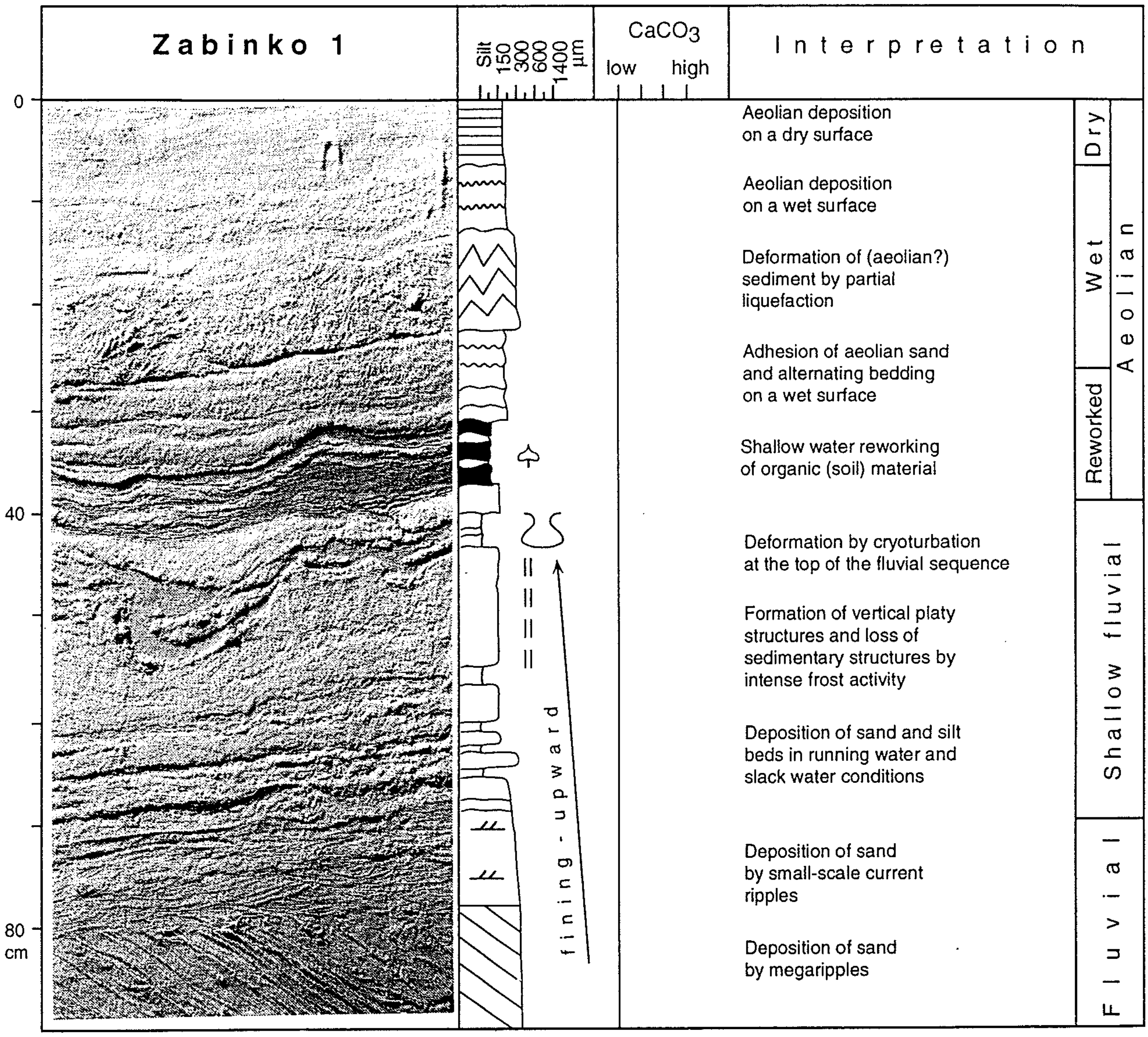


Fig. 5. Photograph and interpretation of lacquer peel Żabinko 1 (location of peel in Fig. 4). The peel shows the fining upward top of the braided system (units I and II) and the base of aeolian unit IV with reworked soil material from unit III

ice advance (Leszno Phase, ca. 18.4 ka BP). The fluvial sediments in the exposure have formed after ice retreat and therefore must be younger than ca. 20 ka BP. According to Kozarski (1983) the drainage system in the pradolina (ice marginal valley) was in operation from the Poznań Phase onwards (ca. 18.4 ka BP) until the beginning of the Late Vistulian (Weichselian) Lateglacial. A terminus ante quem for braided river deposition (unit I) is obtained from the lacustrine facies of unit III (Figs. 4 and 6) which, according to Tobolski (1988), dates from the Bølling (12,630 ± 160, 12,510 ± 330 BP).

TABLE 1. LIST OF C-14 DATES USED IN THE TEST AND FIGS. 4 AND 12

Lab. No	Material	Location	C-14 years BP
GrN 16179	Mammal rib bone	sandpit, unit III	12,330 ± 370
GrN 16177	reworked peat clast	sandpit, unit I	33,700 + 2000/−2600
GrN 16188	sandy black gyttja	476-472 cm core 508	12,190 ± 270
GrN 16189	fine detrital gyttja	452-448 cm core 508	12,040 ± 160
GrN 16190	sandy coarse detr. gyttja	387-383 cm core 508	11,190 ± 170
GrN 16191	brown peat	320-325 cm core 508	10,380 ± 170
GrN 16192	dark brown, sandy peat	300-305 cm core 508	10,380 ± 120
GrN 16193	amorphous peat	248-253 cm core 508	9,950 ± 90

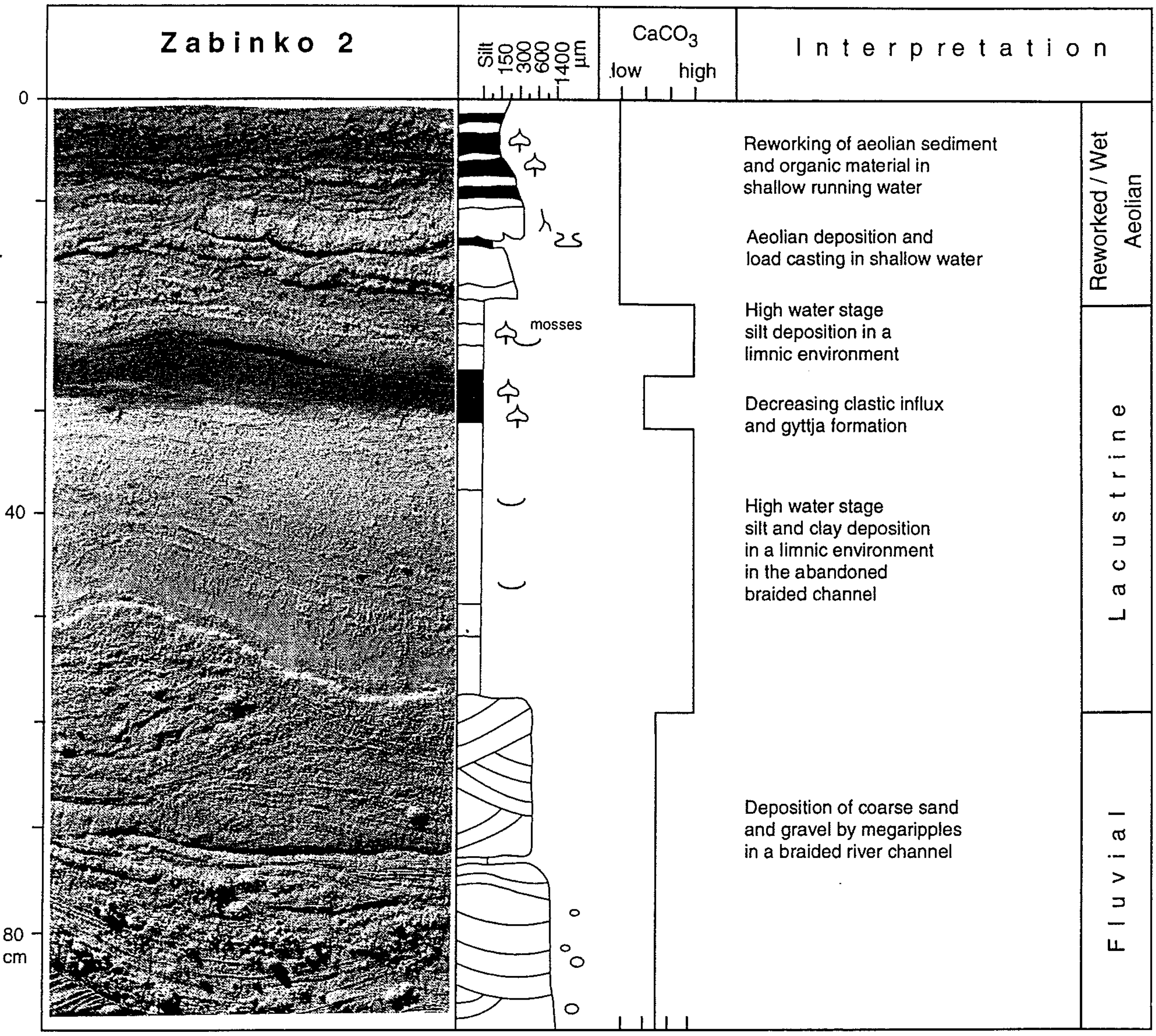


Fig. 6. Photograph and interpretation of lacquer peel Zabinko 2 (location of peel in Fig. 4). This peel shows the abrupt transition of the braided unit I to the lacustrine unit III of Bølling age

Unit II

This unit is found at ca. 61-64 m a.s.l. (Fig. 4). It is genetically related to unit I, since it forms the fine-grained continuation of channel unit I. The sedimentary structures are dominated by wavy bedding and small-scale cross-lamination in fine to medium sand. This facies has been formed in a fluvial environment with, in comparison to unit I, lower current velocities. Locally, alternating bedding of fine to medium sand and loamy fine sand occurs, which points to intermittent flow and more or less standing water conditions following high water levels on the floodplain. This alternation is very well reflected in the grain-size distribution pattern (Fig. 9: samples 4-5-6). The fine-grained part has a modal grain-size of 3.35 à 3.4ϕ and a high percentage of coarse silt (16 à 21%), while the coarse part has a modal size of 1.15 à 1.4ϕ. Two individual sedimentary environments are reflected in this grain-size distribution pattern: strong flow of short duration is quickly alternating with waning flow. The coarse component is identical to the bedload component of unit I. The main (fine) component is finer-grained than the finer part of unit I sediments. It is interpreted as a deposition from suspension in slow flow with only minor settlement of clay in standing water.

The overall geometry of unit II in the exposure permits to conclude that unit II represents a large-scale bar (3 m high) overlying and lying adjacent to the braided river channel sediments (unit I). Repeti-

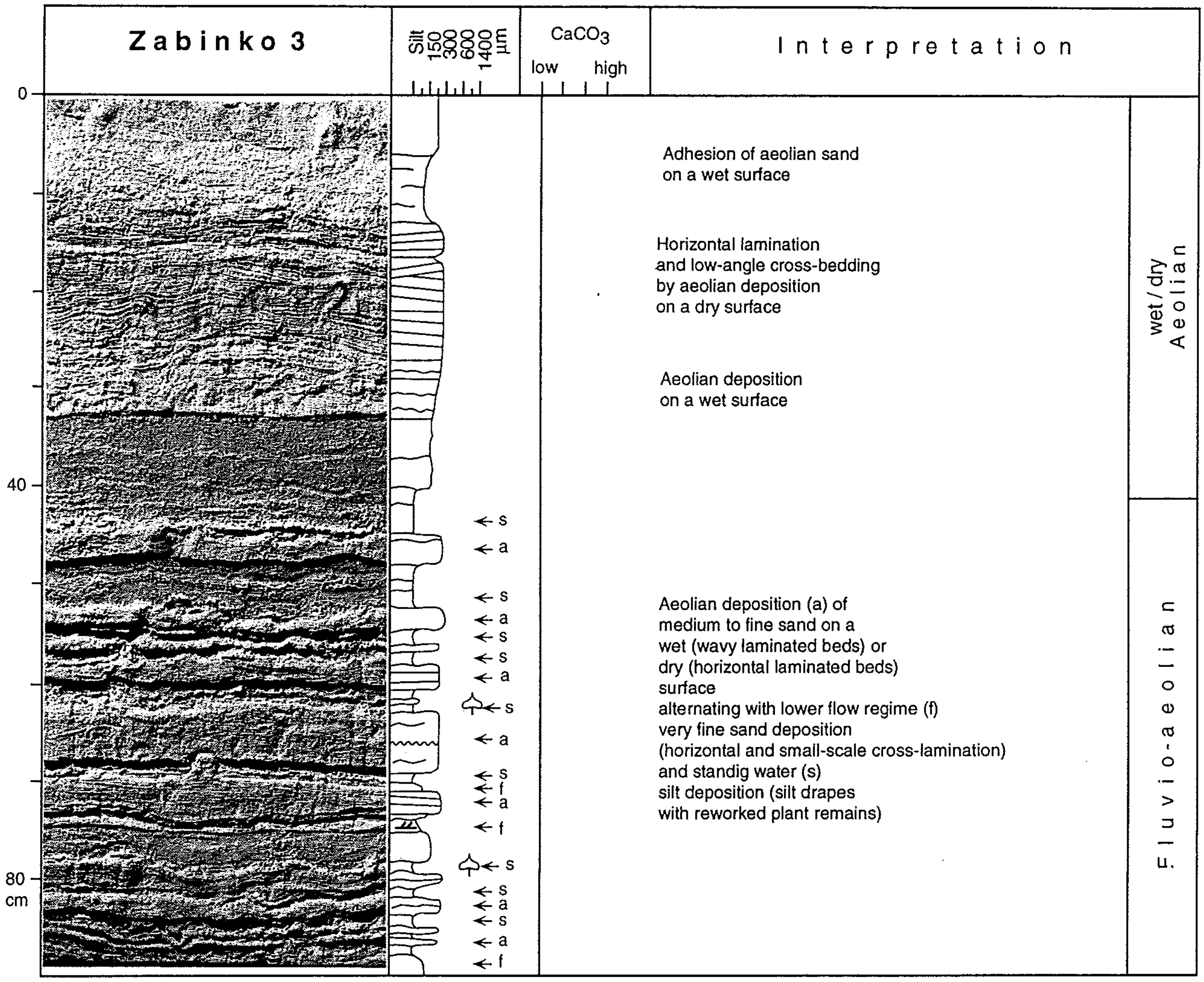


Fig. 7. Photograph and interpretation of lacquer peel Żabinko 3 (location of peel in Fig. 4). The peel had been made in the fluvio-aeolian upper part of braided unit II

tive exposure of the bar surface is evident from the fact that deep syngenetic frost cracks or perhaps initial ice-wedge casts occur in unit II. These cryogenic structures point to a mean annual air temperature (MAAT) of –1 to –4°C or lower during the formation of the cracks and its surrounding sediments. Kozarski (1991) estimated a MAAT of –6 to –8°C for this period. Permafrost may have been present locally.

In the upper part of unit II a gradual change in sedimentary environment from fluvial to aeolian is deduced from the detailed study of the lacquer peels (Figs. 7 and 8). Lacquer peel Żabinko 3 (Fig. 7) contains alternating bedding of sand and silt at the base. The silt beds are mostly massive and locally contain some plant debris. They are interpreted as slack water deposits on the interchannel bar associated with high river discharges. Sedimentological evidence for current flow is found in thin cross-laminated sets of fine sand. Most of the sand beds, however, are fine to medium grained and do not contain any cross-lamination. They are dominated by wavy bedding, crinkly bedding and low-angle or horizontal lamination. In accordance with Schwan (1988) these bedding types are interpreted as being formed by aeolian deposition on a wet and dry surface respectively.

From the point of view of grain-size characteristics (Fig. 9: samples 7-8-10) they are on the average coarser than the underlying samples of unit II. They show also a characteristic bimodality, but consisting of two different components than those composing the lower part of unit II. The major component has a modal size of 1.9 or 2.4ϕ, while the minor component has a modal size of 3.35ϕ. The resulting mean grain-size varies between 2 and 2.6ϕ according to the rate of mixture. The coarser component has the same characteristics as the dune sands of unit IV (see below). Thus, aeolian activity is clearly expressed in the upper part of unit II. The finer component is similar to the fine part of the

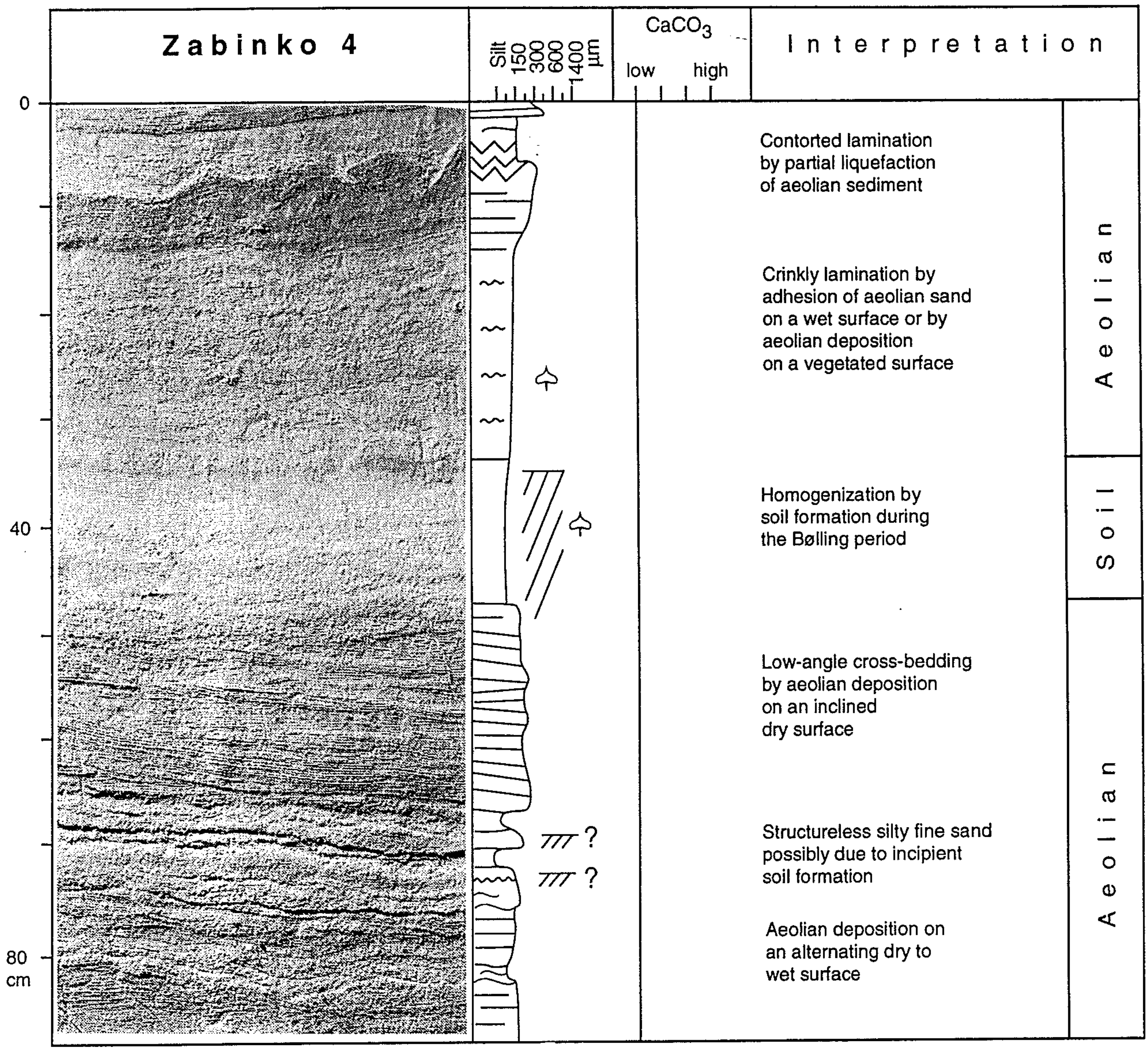


Fig. 8. Photograph and interpretation of lacquer peel Żabinko 4 (location of peel in Fig. 4). The peel demonstrates the aeolian deposits in the top of unit II, the Bølling soil and the overlying dune sediments (unit IV)

braided channel deposits of unit I. Therefore, this sediment type of unit II is interpreted as resulting from shallow flow reworking especially aeolian sands and a fluvio-aeolian genesis (for the lower part of lacquer peel 3) is suggested. In the fluvio-aeolian series occasionally thin aeolian beds occur according to their identical grain-size distribution as the dune sands (sample 9).

In the upper part of lacquer peel Żabinko 3 (Fig. 7) and the lower part of Żabinko 4 (Fig. 8) crinkly lamination, wavy bedding and low-angle cross-bedding associated with aeolian deposition on a wet to dry surface are dominant. This interpretation indicates that during the final stage of the existence of the braided system on the bifurcation terrace (unit I and II) aeolian processes became more and more important. On the highest interchannel bars aeolian deposits accumulated as thin sand sheets or low dunes.

The existence of aeolian sediments in the upper part and on top of the braided system of the bifurcation terrace has previously been described for this region by Antczak (in Kozarski, Tobolski 1981 p. 26-28). She reported the presence of coversands on central bars of the braided system. Furthermore, sand grain roundness, attributed to abrasion during aeolian transport, appeared to be higher (better rounded) in the topstratum deposits when compared to the underlying braided channel sediments. Unit II is capped by the palaeosol of unit III (Fig. 4).

Unit III

This unit is found at an altitude of 60,5 to 64 m a.s.l. Unit III is partly developed as a soil and partly as a lacustrine deposit (Fig. 4). Dates from the lacustrine deposit range from 12,630 ± 160 BP in the bottom to 12,210 ± 130 BP in the top of the sequence (Nowaczyk 1986; Tobolski 1988). The palynological evidence as presented by Tobolski (1988) shows a *Betula* dominated phase (the *Betula-Hippophaë* LPA zone), correlated with the Bølling, in the lacustrine deposits at the base of the infill. During this phase the abandoned river branch formed a shallow basin with standing open water bordered by tree birches (*Betula "alba"*, including *B. tortuosa* and *B. pubescens*) and willow shrub with an understory of *Carex rostrata* and *Carex* section Flava, mosses and Equisetum. Insect assemblages (Lemdahl 1991) indicate an average July temperature of 14-15°C. Subsequently a hydroseral succession led to peat deposition, a strong local presence of *Betula* and an expansion of *Pinus* (the *Betula-Pinus* LPA zone). The termination of the infill again is formed by a lacustrine deposit and it is concluded (Tobolski 1988; Lemdahl 1991) that a deepening of the sedimentary basin was responsible for this process.

The soil of unit III is formed on the high interchannel bars of unit II (Figs. 4 and 8) and is characterized by a 2 cm thick Ah horizon underlain by a 10 cm thick light gray, somewhat bleached eluvial horizon. An illuvial B horizon has not been observed. Iron mottles in the lower part of the bleached horizon indicate occasional stagnant conditions (gleyic phenomena) during the soil formation. This soil can be classified as a Gleyic/Haplic Arenosol (FAO 1988) or Cryaquent/Cryopsamment (USDA 1983). The occasional water saturation of the soil in otherwise very permeable parent materials may be explained by the presence of annual or perennial soil ice lenses which hampered the drainage during the melting season. Dates on the soil of unit III (12,680 ± 90, 12,390 ± 70, 12,130 ± 140 BP) are provided by Nowaczyk (1986). An additional date of 12,330 ± 370 BP (GrN-16179, table 1) was obtained by us from a bone fragment lying on top of soil unit III (see Fig. 4). All dates are in good agreement with a Bølling age for the palaeosol.

According to Kozarski (1991) the permafrost that was present during the deposition of units I and II, persisted during the formation of unit III. The latter author states that the existence of a shallow lake environment overlying highly permeable deposits was only possible when permafrost was present in the underlying coarse-grained deposits. Supporting evidence for the presence of relic permafrost during the Bølling comes from dead-ice structures in the vicinity (indicated by the letter w (=water/marsh) in Fig. 3). Their location on the bifurcation terrace proves that they are younger than the terrace itself. Final melting of the dead-ice occurred after the bifurcation terrace had been abandoned, otherwise the depressions would have been filled by fluvial deposition. The abandonment of the bifurcation terrace has been dated rather precisely at 12,630 ± 160 BP (Tobolski 1988, base of lacustrine unit III in Żabinko sand pit) or even at 12,190 ± 270 BP (Żabinko channel, see palaeobotanical results). Therefore, melting of the dead-ice bodies should have occurred later than the Bølling period. The disappearance of the permafrost/dead-ice seems to coincide with a change in fluvial regime of the Warta river, since following the Bølling phase the Warta abandoned the bifurcation terrace and established its large meandering pattern. Simultaneously the tendency towards aggradation of the bifurcation terrace river systems was replaced by incision of the large meander system.

Unit IV

Unit IV is found above 61 m a.s.l. The highest dune ridges are over 80 m a.s.l. Only the lower part (ca. 1 m) is presented in figure 4. Unit IV is part of a large dune field (ca. 10 km^2) overlying the bifurcation terrace (see Fig. 3). Its source area is the bifurcation terrace ca. 4 km west of the Żabinko sand pit. The dune field is a complex of coalescing parabolic dunes. The parabole shape and the steep eastern lee side of the dunes point to a westnorthwesterly wind (ca. 282°).

The maximal age of unit IV can be derived from the ^{14}C-dates of unit III underlying unit IV (Nowaczyk 1986). The youngest date of unit III, 12,130 ± 140 BP, is taken as a terminus post quem for the start of the aeolian deposition. According to Nowaczyk (1986) the parabolic dunes of Żabinko, in the absence of an Allerød soil in the dunes, have been formed exclusively during the Older Dryas period. In fact the minimal age of unit IV is more or less unknown. Only a Holocene buried soil (1010 ± 110 BP) was found in the slip faces of the parabolic dune (Nowaczyk 1986). Recently, within the dune sands a palaeosol has been observed that is provisionally correlated with the Allerød soil (Kozarski, oral communication) based on the comparison with other Late Vistulian inland dunes (Manikowska 1977, 1985; Nowaczyk 1986).

The lower part of unit IV is overall horizontally bedded. In more detail (lacquer peels Figs. 5, 6, 8) the sedimentary structures are dominated by wavy

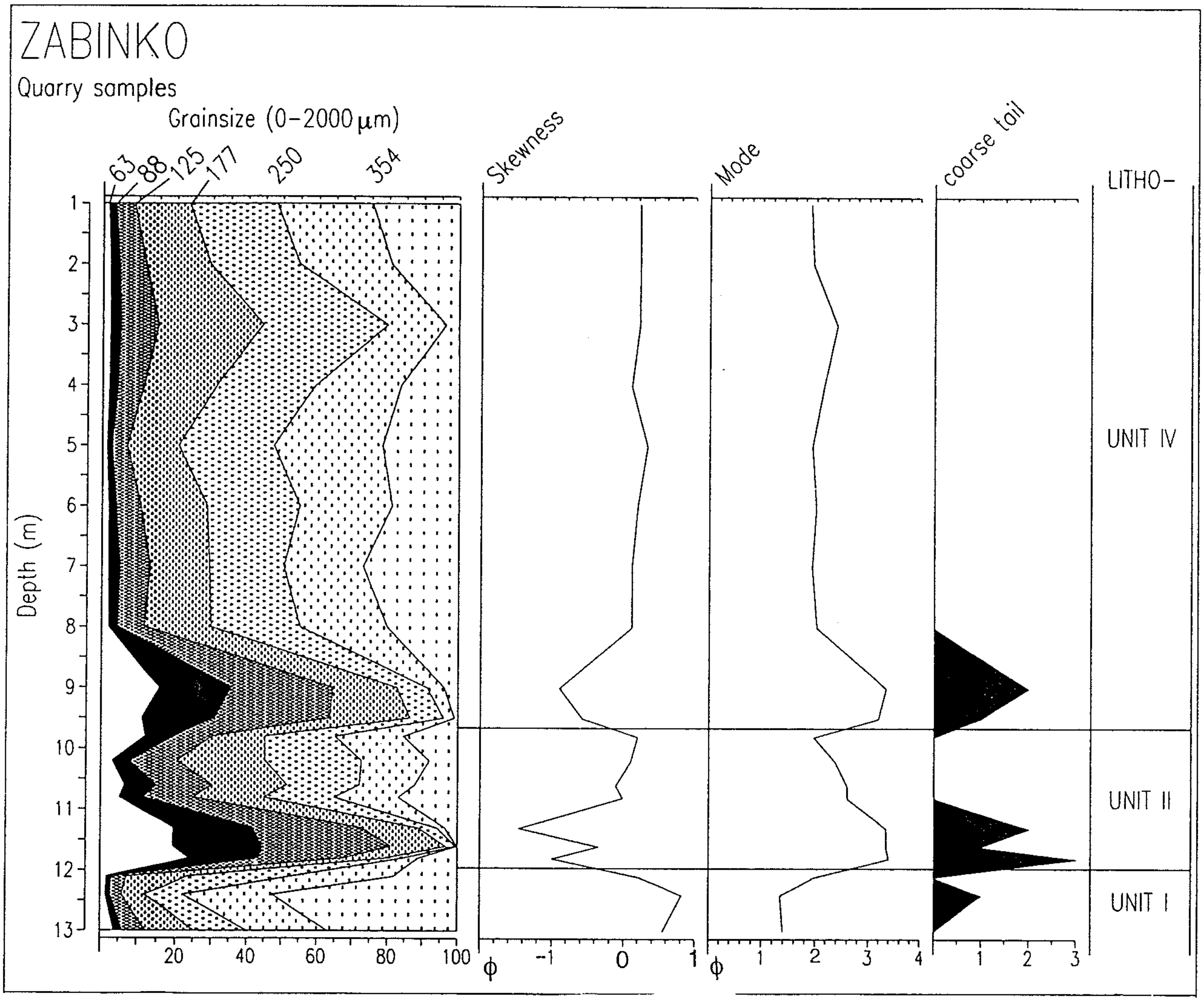


Fig. 9. Grain-size distribution of the fluvial and aeolian sedimentary units in the Żabinko sand pit. Skewness calculated between 62 and 2000 μm. For the coarse tail arbitrary units are used. The position of the samples indicated in Fig. 4

bedding, crinkly lamination, contorted bedding, low-angle cross-bedding and horizontal lamination. The first three bedding types are generally associated with aeolian deposition on a wet or damp surface (Schwan 1988). The latter two types are typical for dry aeolian deposition. The dry aeolian bedding types become more important higher in the sequence (Fig. 5). Locally, in the former topographic depressions of unit III, reworking by shallow running water has been established (Figs. 5 and 6). This reworking process locally affected the Bølling soil (unit III) that was redistributed as humic laminae in the fine sand at the base of unit IV.

Grain-size characteristics of the sediments directly overlying the Bølling soil demonstrate that they are badly sorted and obviously consist of different components (Fig. 9: samples 11-12). The dominant fraction is identical to the fine fraction of the 'fine-grained laminated fluvial deposits' (lower part of unit II) as far as the grainsize is concerned. It is composed of a very fine, slightly silty sand with a modal size of 3.2 à 3.35ϕ. A small fraction shows the characteristics of the overlying 'dune sands' with a mode of 2ϕ. A third, coarse component is small but clearly present. The macroscopic structures in this deposit point to a local reworking of the Bølling soil (Unit III) and the underlying sands (Unit II). Unlike the laminated fluvial deposits of unit II, this sediment cannot be the result of overbank deposition because of its high morphological position. Instead, surface runoff could produce a similar sorting of the sediment leading to the major component of very fine sand, with a small amount of coarse material (lag deposit) and a certain admixture of aeolian sand from the approaching dune. Alternatively, instead of surface runoff and local reworking the deposition of silty fine sand in horizontal beds can be explained by aeolian sorting processes in front of the advancing dunes. Grainfall deposits falling from suspension at the lee side of a parabolic dune become finer and better sorted down the lee slope (Ahlbrandt, Fryberger 1982 p. 30-31).

The upper part of unit IV is dominated by very large-scale cross-bedding formed by dune slip face progradation. The dune foresets dip to the east and they indicate, in agreement with the large-scale dune morphology, a westerly wind during their formation (see also Nowaczyk 1986). Grain-size analyses of unit IV (Figs. 4 and 9: samples 13 to 20) show an almost identical grain-size distribution in particular by the unimodal composition, the good sorting, the absence of any sediment <32 μm and a skewness between .10 and .32ϕ. This characteristic unimodal grainsize distribution without a coarse 'tail' indicates that the sediment is completely composed of the saltation population with absence of any rolling population. The modal grainsize is mostly 1.9 to 2.05ϕ, except for two samples which are somewhat finer (respectively 2.15 and 2.4ϕ). This mean grain-size is in agreement with the general grain-size reported by Nowaczyk (1986) from the same dune field.

Considering unit IV as a whole the finer grained horizontally bedded lower part and the overlying coarser grained large-scale slip faces can be interpreted as a drying upward and coarsening-upward sequence formed by the progressive migration of the dune field. The fine-grained, mostly horizontally bedded lower meter of the dune is interpreted as the distal aeolian facies of the dune at the lee side, this is downwind of the slip face. It strongly resembles the horizontally bedded wet interdune deposits described by Ahlbrandt, Fryberger (1982). The fine sediment, which was deposited by grainfall from suspension at the lee side of the prograding dune, was trapped on the vegetated and locally damp surface (Fig. 8). The surface wetness was caused on the one hand by the fact that the aeolian sand migrated and prograded over an existing wet palaeosurface and on the other hand by the growth of the dunes. Figure 6 demonstrates that the lacustrine environment of unit III was still present at the start of the sand influx. The first aeolian sediments were deposited in shallow water and some reworking and loading took place. The return to lacustrine deposition in the top of unit III (Tobolski 1988) may be explained by hydrological changes triggered by the expansion of the dune field. When the major parabolic dune bodies migrated close to the Żabinko site, they will have lifted the local groundwater level within the dune body as well as in front of the dunes (eg. Zagwijn 1984). The raised groundwater level in the dunes will have resulted in wet conditions in front of the dunes and even groundwater seepage and surficial flow may have occurred.

As has been argued above (unit III), dead-ice bodies/permafrost were still present in the pradolina

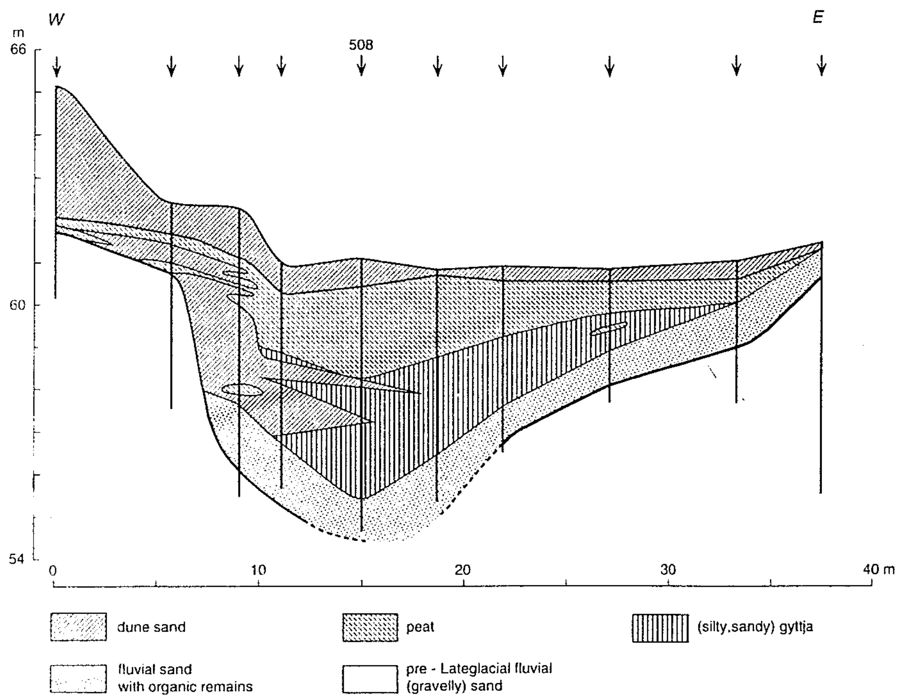


Fig. 10. Cross-section over the abandoned Żabinko channel of the transitional system (for location, see Fig. 3). Core 508 has been analysed on pollen, macrobotanical remains, loss on ignition and grain-size

during the formation of the bifurcation terrace and the surface of the terrace will have been rather wet in the summer months, due to a combination of melt water and impeded vertical drainage. The final disappearance of the permafrost will have resulted in a drying of the terrace surface and especially in the large up to 3,5 m high interchannel areas on the bifurcation terrace the groundwater level will have dropped. This process may have triggered the aeolian phase following the Bølling soil/lacustrine unit III. It seems likely that the deflation started on the former interchannel bars, forming the source areas of the post-Bølling dunes. Another hypothesis is to invoke the vertical river incision after the abandonment of the braidplain to explain the lowering of the groundwater table (Vandenberghe et al. 1987).

Morphology and infill of the Żabinko transitional channel

Due east of the parabolic dunes a palaeochannel is present (Fig. 3). It is part of a transitional phase between the braided system of Pleniglacial/early Lateglacial age and the palaeomeanders of Allerød age (Vandenberghe et al. 1994). Its palaeogeographical position with respect to the parabolic dunes pre-eminently offers the opportunity to trace and date aeolian activity on the braidplain to the WNW. A series of borings was made, oblique to what now seems the length axis of the palaeochannel, in order to establish its morphology and to locate the site with the thickest and oldest deposits (Fig. 10).

The subsoil, in which the channel has incised, consists of bedded heterogeneous gravelly sand and gravel. The upper part is a generally finer-grained sand with short fining-upward sets. These subsoil sediments are interpreted as braided fluvial deposits of the Late Pleniglacial system.

The base of the channel has been eroded to ca. 54 m a.s.l. which is about 6 m below the base of the palaeochannel in the Żabinko sandpit (see Fig. 4). The channel has a more confined character than the channels of the previous braided system, while the slight asymmetry points to some lateral migration. It represents the initial stage in the transformation of that braided system. Obviously, this evolution started with significant erosion of the channel bed. The lowest unit of the channel fill consists of laminated sands with organic remains. Towards the top of this unit and towards the channel sides they alternate with clays and silts. This unit represents the last phase of clastic deposition in the channel. At the time the channel became inactive the coarser-grained bedload was covered with fines. The channel was filled first with sandy, silty or clayey, laminated gyttja (max. 3 m thick) and later on with peat. The gyttja grades gradually into the overlying peat (max. 2.25 m thick) that shows a succession from reed peat at the base to moss and sedge peat and to sedge and fen wood peat at the top. At the west side of the channel this organic unit interfingers with sands which are partly purely aeolian and partly reworked (see below). Boring 508 was cored with a 6 cm diameter auger and subsequently subsampled at 2 cm intervals at the laboratory.

Grain-size characteristics of the Żabinko channel fill

According to the grain-size distribution (Fig. 11) three sediment facies are distinguished:

a. Heterogeneous deposits constitute the main part of the channel fill: (320-475 cm). This badly sorted facies contains mainly three inorganic components:

a1. a silty-clayey mixture,

a2. very fine sand (mode 3.1 to 3.35ϕ),

a3. coarse sand (mode 1.3ϕ).

The relative amounts of these components very considerably. Their source may be derived by comparing them with the fluvial facies in the nearby Żabinko sand pit (Fig. 4: units I and II). The a3-component corresponds with the high energy river flow (unit I) and is contrasting with deposition from suspension during slow flow (a2) like in the 'laminated fine-grained deposits'of unit II. The very fine-grained a1-component is the result of deposition from suspension in standing water. It is further characterized by accumulation of organic matter more than in the two other components. Such high amounts of silt and clay have not been found outside the channel.

Mixtures of the three components occur in all rates but they are not randomly distributed over the infill. A number of fining-upward sequences is recognized starting with a prominent amount of coarse or fine sediment (a3- or a2-components) and a small amount of very fine and organic material (a1-component). In an upward direction this ratio is gradually reversed. This corresponds with a change from short periods of relative strong flow to weak flow and standing water. Such fining-up cycles occur from 475 to 444 cm, 444 to 425 cm, 425 to 400 cm and 380 to ca. 320 cm. The latter corresponds in time with the start of the Younger Dryas.

The coarse component (a3) is clearly derived from the deposits of the Pleniglacial braided river system, in which the channel is eroded. The very

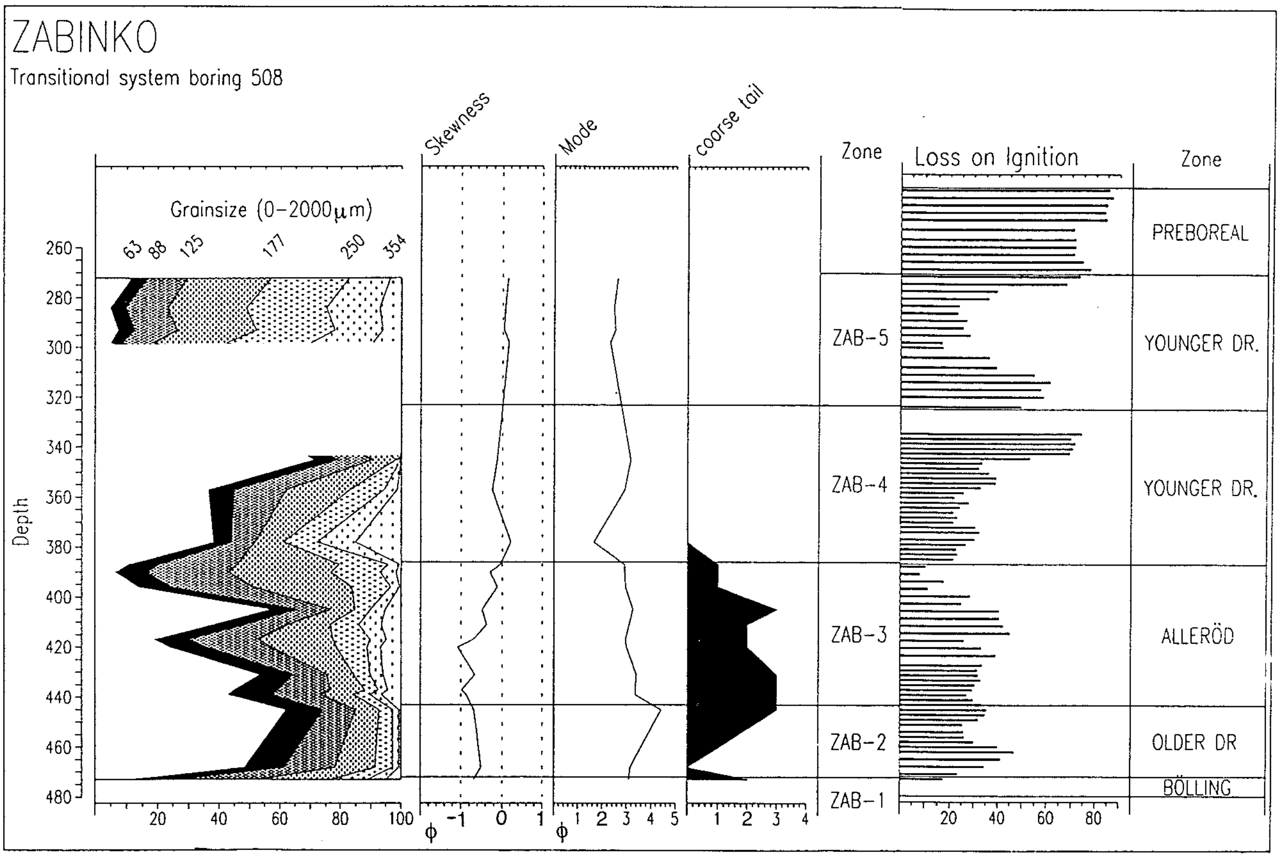


Fig. 11. Loss on ignition (LOI) and grain-size distribution of core 508 from the Żabinko channel (for location, see Fig. 10). Skewness calculated between 62 and 2000 μm). For the coarse tail arbitrary units are used

fine sands (a2) are interpreted as the result of reworking of the finer-grained subsoil deposits (e.g. the upper part of the braided sequence, fluvio-aeolian and aeolian deposits: units I and II described from the Żabinko pit).

b. A quite homogeneous layer between 400 and 380 cm, the upper part of the Allerød, is different from the other sediments in this channel. It is a fine sand (mode 2.9φ) which is different from the dune sands by its general finer texture, the small 'coarse tail', the different skewness and the presence of some material <32 μm. It is interpreted as a channel fill by settlement of sandy suspension material in a waning flow. It is slightly coarser than the similar sediment in overbank position (fine component of the 'laminated fine-grained fluvial deposits' of unit II). The 'coarse tail', representing 5 to 20% of the deposit, probably corresponds with dune sands.

c. The sediment between 300 and 275 cm has its modal size between 2.3 and 2.5φ, a skewness of .05 to .16φ, no 'coarse tail' and few sediment <32 μm. These characteristics are very similar to the fine-grained samples of the parabolic dune, although some more silt is present in the channel. It is concluded that the grain-size distribution at this depth provides distinct evidence for aeolian activity in the upper half of the Younger Dryas. Around 275-270 cm the sediment becomes somewhat finer: it is partly reworked and forms the transition to the upper organic bed.

The sediment sequence represents the infilling of an abandoned channel which functioned only during peak discharges in the active channel(s). Several depositional cycles may be distinguished. Occasionally they start with a short phase of rather quick flow, followed by slow flow and ultimately stillstand of flow during which also organic matter could accumulate. One layer of pure dune sand is present (300-275 cm) and one layer with a minor admixture of aeolian sand (400-380 cm).

With respect to the fine sandy component in the channel infill (a2-component) an alternative interpretation is proposed, which takes aeolian sorting processes at the lee side of the parabolic dune (e.g. Ahlbrandt, Fryberger 1982) into account. This a2-component may than be interpreted as a distal aeolian facies, deposited in a lacustrine environment, similar to the horizontally bedded fine sand at the base of the parabolic dune in the Żabinko sand pit (Fig. 4: unit IV). A possible aeolian source for the fine sand in the channel fill is furthermore supported by: 1) the geomorphological position of the palaeochannel directly adjacent to the dune slipface (see Figs. 3 and 10), 2) the cross-sectional geometry of the channel infill (see Fig. 10) in which aeolian dune sands interfinger with lacustrine gyttja and peat and finally 3) the general coarsening-up trend in the grain-size analyses (Fig. 11), which could possibly reflect the gradual progradation and encroachment of the parabolic dune.

In the basal part of the fill (385-470 cm) the finer-grained grainfall sediments, that are transported in suspension (Fig. 11: 63-105 m, part of 105-210 μm), are relatively important. Above 385 cm and especially between 270-300 cm the component transported by saltation (Fig. 11: part of 105-210 μm and 210-420 μm) increases strongly. The latter samples resemble in grain-size the samples of the dune slipfaces in the Żabinko pit. Such slipfaces are formed by avalanching of sand transported predominantly by saltation processes (Ahlbrandt, Fryberger 1982).

Palaeobotanical record of Żabinko channel, core 508

Methods

The preparation of the palynological samples followed the procedures as described by Faegri, Iversen (1975). A heavy liquid separation was performed using $ZnCl_2$ with a density of 2.0. Pollen concentration values were obtained by adding *Lycopodium* spores to the samples according to the method of Stockmarr (1975). The pollensum for the percentage diagram consists of AP and upland herbs. Macrobotanical samples from the same levels were boiled in KOH 5% and subsequently strained through a sieve with 210 × 210 μm meshes.

A total of six levels from the infill have been dated on bulk samples (Centre for Isotope Research, Groningen). They represent the major boundaries as they appear in the palynological record.

The remaining material after palynological and macrobotanical subsampling was used to perform loss on ignition (LOI) measurements by burning for 5 hours in an oven at a temperature of 550°C. The minor presence of $CaCO_3$ in the sediments is believed to have only a marginal effect on the LOI values. Besides, for a number of levels the grainsize distribution has been determined by using a laser particle sizer.

Inferred vegetational history

Six local pollen assemblage zones (LPAZ) have been established based on the fluctuations between AP and NAP (Fig. 12). They have been prefixed by the site designation ZAB and numbered from bottom to top. The macrobotanical record follows the palynological zonation (Fig. 13).

Zone ZAB-1, 477-473 cm

Chronostratigraphy: a date of 12,190 ± 270 BP has been obtained from the bottom sediments. Biostratigraphically this zone is correlated with the termination of the Bølling.

Lithology: brown sand grading into a black sandy gyttja at 475 cm.

This zone represents the terminal phase of fluvial activity in the transitional gully. The relatively high *Pinus* percentages and the presence of *Juniperus* and *Populus* in combination with a declining trend in the *Betula* curve, demonstrates similarity with the upper spectra in the nearby infill of a channel of the braided system, dated to 12,210 BP (Tobolski 1988). Macrobotanical information from this zone is poor.

Zone ZAB-2, 473-443 cm

Chronostratigraphy: this zone embraces the time interval between ca 12.2 ka and 12 ka BP. This zone correlates with the Older Dryas.

Lithology: black sandy gyttja grading into a slightly sandy gyttja at 456 cm.

With respect to the preceeding zone, ZAB-2 registers a considerable opening of the vegetation cover and the floodplain became populated by a heliophilous pioneer shrub vegetation consisting of *Juniperus*, *Populus* and small birches (*B. nana*, *B. humilis*?). Macroremains of *Pinus* demonstrate that stands of pine occurred in the vicinity of the site, possibly on more elevated positions (dunes?) in the floodplain beyond the reach of inundations.

Upland pollen taxa like *Artemisia*, *Chenopodiaceae*, *Centaurea*, *Helianthemum*, *Papaver*, *Linum* and *Jasione* indicate heliophilous pioneer conditions. This sudden opening up of the Boreal birch pine wood may be attributed to dry soil conditions related to the final disintegration of relic permafrost and a simultaneous further oganinization of the drainage system of the Warta river (see also unit III). On the abandoned bifurcation terrace a process of recolonization started.

At least part of the *Gramineae* during this zone derived from a *Phragmites* belt (see macrobotanical record, Fig. 12), that bordered on open water. The *Phragmites* vegetation was intermingled with elements from the Filipendulion (*Filipendula*, *Rubiaceae*), *Iris pseudacorus* and *Carex* species.

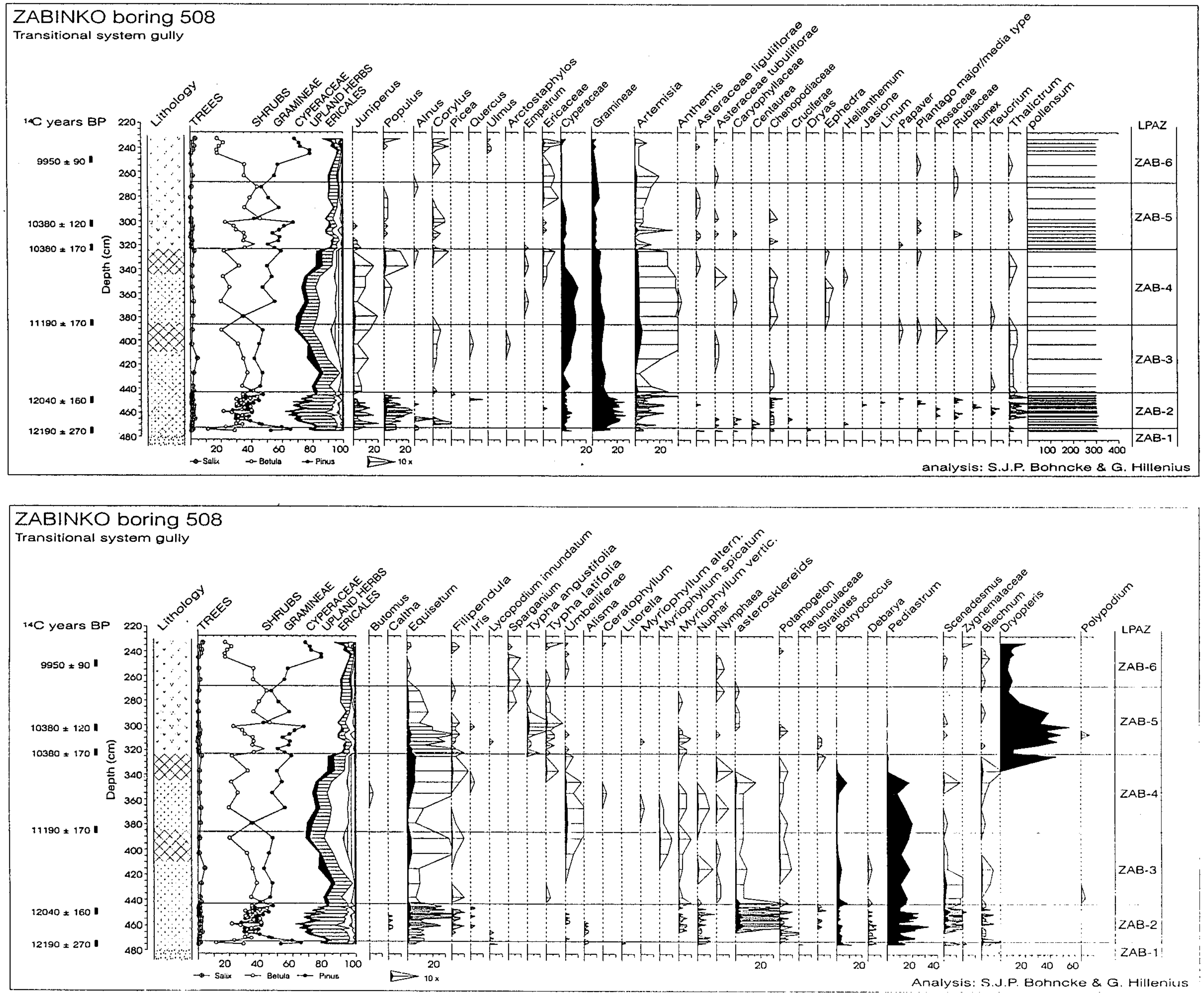
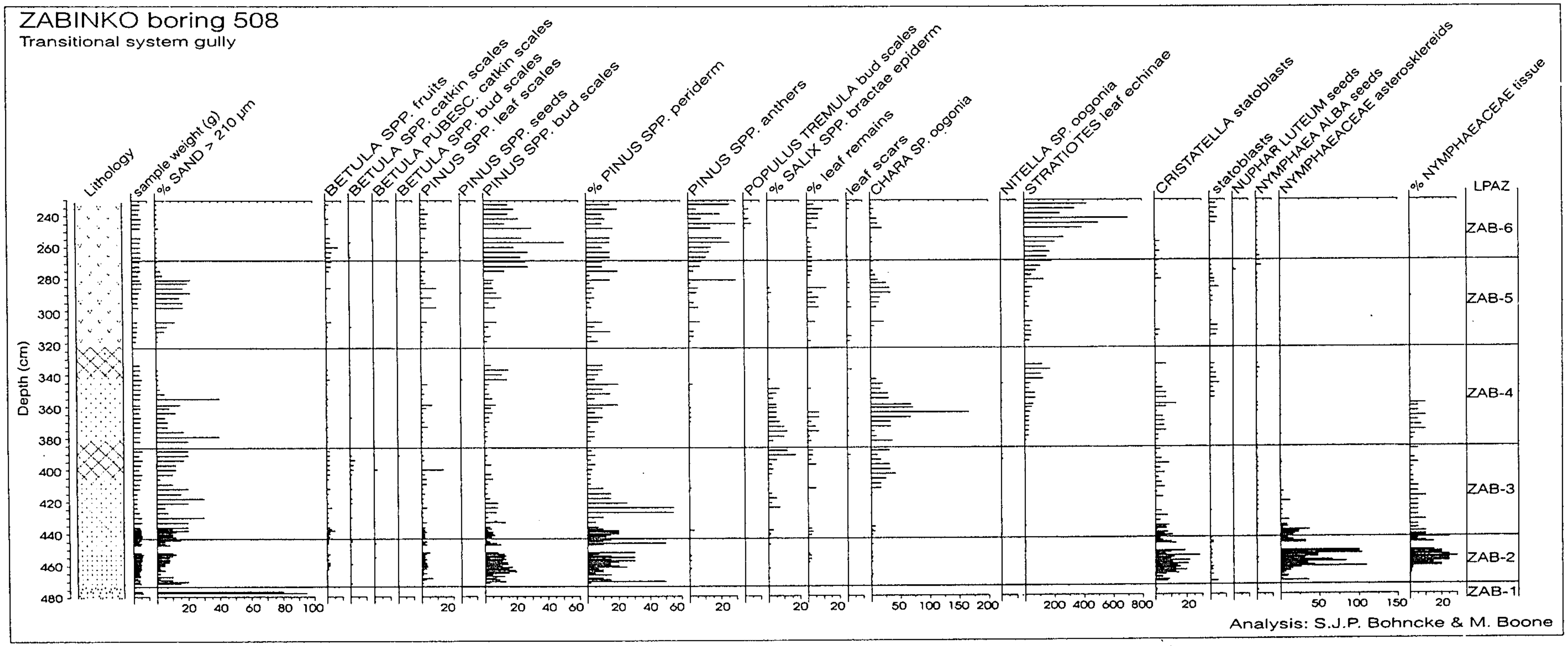


Fig. 12. Pollen diagram of core 508 from the Żabinko channel (for location, see Fig. 10)


ZABINKO boring 508
Transitional system gully
Lithology
sample weight (g)
% SAND > 210 µm
BETULA SPP. fruits
BETULA SPP. catkin scales
BETULA PUBESC. catkin scales
BETULA SPP. bud scales
PINUS SPP. leaf scales
PINUS SPP. seeds
PINUS SPP. bud scales
% PINUS SPP. periderm
PINUS SPP. anthers
POPULUS TREMULA bud scales
% SALIX SPP. bractae epiderm
% leaf remains
leaf scars
CHARA SP. oogonia
NITELLA SP. oogonia
STRATIOTES leaf echinae
CRISTATELLA statoblasts
statoblasts
NUPHAR LUTEUM seeds
NYMPHAEA ALBA seeds
NYMPHAEACEAE asterosklereids
% NYMPHAEACEAE tissue
LPAZ
ZAB-6
ZAB-5
ZAB-4
ZAB-3
ZAB-2
ZAB-1
Depth (cm)
240
260
280
300
320
340
360
380
400
420
440
460
480
Analysis: S.J.P. Bohncke & M. Boone

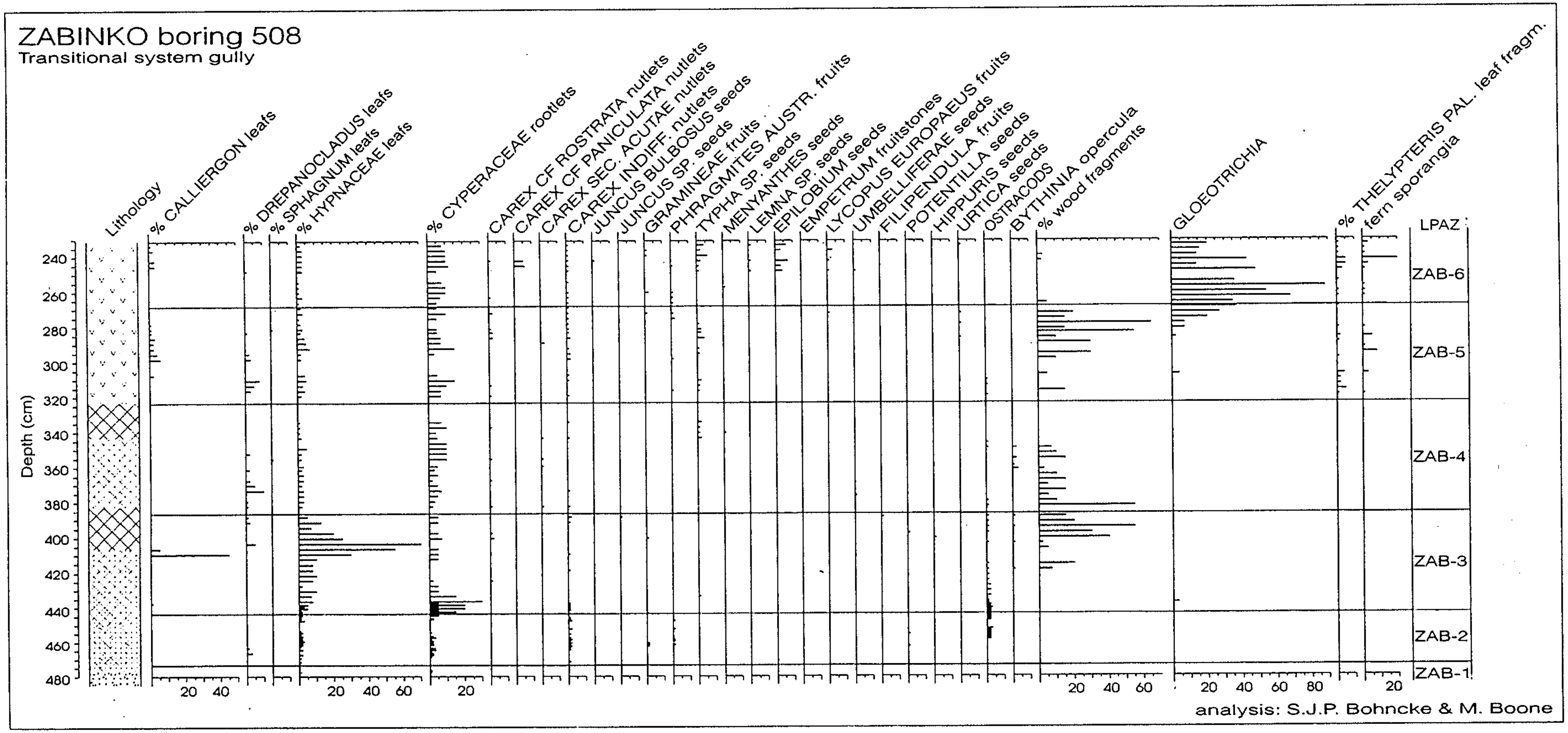


Fig. 13. Macrobotanical diagram of core 508 from the Żabinko channel (for location, see Fig. 10)

Locally, a diverse aquatic vegetation was present consisting of *Nymphaea alba* (seeds), *Nuphar lutea* (seeds and pollen), *Stratiotes aloides* (pollen and leaf echinae), *Potamogeton* spp., *Caltha palustris* (pollen), *Alisma plantago aquatica*, *Myriophyllum verticillatum* and in low frequencies *Characeae* (oogonia). The occurrences of these aquatics imply that summer temperatures have not changed compared with the previous Bølling period (Lemdahl 1991) and reached maximum values of ca. 14°C.

The aquatics are indicative for both seepage conditions providing iron-phosphates as well as carbonates to the basin as well as a regular input of nutrient rich water possibly supplied during peak discharges of the then active meandering system. The occurrence of reworked pollen (*Corylus*, *Alnus*, *Quercus*) are ascribed to this process.

Towards the top of this zone the floodplain became colonized by tree-birches and the light requiring species like *Juniperus* and *Populus* became shaded out. Locally the decline in the pollen curves of the aquatics and an increase in the *Carex* spp. nutlets and mosses (see Fig. 13) indicates a hydroseral succession. Both processes can be related to a (temporary) decline in the inundation frequency from the then active fluvial system.

Zone ZAB-3, 443-386 cm

Chronostratigraphy: this zone embraces the time interval between 12 ka and 11.2 ka BP and represents the Allerød period.

Lithology: slightly sandy fine detrital gyttja grading into a coarse detrital, sandy gyttja at 408 cm.

Initially a further colonization of the floodplain led to an increase in tree birches and pine and a decline in the *Artemisia* curve. A more stable landscape may be deduced with initial soil development and increased evapotranspiration by the vegetation cover. This greatly reduced seepage to the basin, which is reflected in the temporary decline in the *Equisetum* curve.

This meta-stable condition was suddenly interrupted as appears from the rise in the *Artemisia* curve. A return to raw soil conditions may have triggered these environmental changes. Stands of *Betula* on the braidplain diminished and instead *Salix* shrubs (macroremains) were favoured. *Typha latifolia*, that was present in the lower part of this zone (both pollen and seeds), is absent now, although its habitat was present. The disappearance of *Typha latifolia* during the Allerød is a recurrent phenomenom (see also Bałaga 1990) and argues for a decline in summer temperatures during this zone. More specifically, a decline in summer temperatures from 14°C (the lower temperature limit for *Typha latifolia*: Iversen 1954; Kolstrup 1980) to ca. 12°C (based on the *Juniperus*, *Nymphaea* and *Nuphar* curve) may be deduced. This declining summer temperature trend from the end of the Bølling, with superimposed on this signal some minor improvements, is previously established on the basis of the oxygen isotope curves from Greenland (Siegenthaler et al. 1984) and the Gerzensee (Switzerland, Eicher 1979). At Żabinko intensified seasonal frost, as a result of declining temperatures, may be the most likely process responsible for the return to raw soil conditions.

Simultaneously, strong seasonal fluctuations in the lake-level of the abandoned channel or a general decline in the lake-level may be deduced from the sudden increase in pleurocarpe mosses (Fig. 13, 410 cm) and the lithological transition in the infill from fine detrital to coarse detrital gyttja. The soil interphase in the hydrological system became damaged and precipitation resulted in a more direct flow towards the depression and in strong seasonal fluctuations in the lake-level of the abandoned channel. For the fluvial system this resulted in increased peakedness of the discharge, inundations of the bifurcation terrace and deposition of suspension load in the abandoned channels on the bifurcation terrace. Reworked pollen (*Corylus*, *Quercus*) returned to the pollen assemblage. For the aeolian system the degradation of soils by deep seasonal frost or drought, in combination with strong seasonal fluctuations in the ground-water level (phreatic level) resulted in the renewed supply of sand and a reactivation of aeolian activity on the braidplain. Here *Juniperus* found its habitat. The *Juniperus* curve increases in the upper part of this zone.

Aeolian input to the abandoned channel is clearly reflected in the loss on ignition curve (Fig. 11, 400-386 cm) and in the grain-size analyses (peak centred around 390 cm, see below). The presence of *Papaver* and *Plantago* pollen in the upper spectra of this zone is remarkable. It indicates the close presence of dry substratum, more particularly the migrating parabolic dune.

During the phase with aeolian activity seepage conditions returned to the site as is evident from the increase in *Equisetum cf. fluviatilum*, *Myriophyllum spicatum*, *M. verticillatum* (pollen from 400 cm) and *Hippuris*. These conditions may be induced by an increase in the yearly effective precipitation (decline in evapotranspiration) or can be interpreted as an effect of an approaching and possibly enlarged dune body with an internal updoming groundwater level (e.g. Zagwijn 1984). By assuming a nearby groundwater dome, the hydrological gradient and the seepage towards the basin itself increased.

Zone ZAB-4, 386-323 cm

Chronostratigraphy: this zone embraces the time interval between 11.2 ka and 10.4 ka BP and is correlated with the early part of the Younger Dryas.

Lithology: sandy, fine detrital gyttja with a transition to slightly sandy, coarse detrital gyttja at 346 cm.

Biostratigraphically the transition to the Younger Dryas in the area under discussion is marked by a temporary rise in the *Betula* curve after which *Pinus* started to dominate again (Tobolski 1981; Müller 1953; Binka et al. 1991). Among the upland herbs several taxa are in favour of this interpretation; *Empetrum, Chenopodiaceae, Ephedra distachia* and the reappearance of *Populus*. The *Cyperaceae*, that started to increase in the upper part of the preceding zone, show a further increase.

Seepage indicators (*Equisetum, Myriophyllum* spp.) in the bottom part of this zone are nearly absent. Instead *Nuphar* and *Nymphaea* returned to the site, which indicates a rise in the water table and inflow of nutrient rich water. Renewed fluvial inundations of the abandoned channel is confirmed in the grainsize analysis of this interval (Fig. 13, 380-360 cm). Stream velocities during inundations were relatively high (coarse fraction in the grainsize) and may have removed the original lake bottom flora. Pioneer conditions on the lake bottom, indicated by the peak in the *Characeae* (Fig. 13, 370 cm), are evident.

The aeolian input to the channel diminished (grain-size analyses). Wet conditions in the source area (the braidplain west of the site), either caused by increased precipitation and/or incipient permafrost and/or frequent fluvial inundations, may ultimately have hampered the aeolian sand supply to the channel.

A remarkable change took place in the upper part of zone ZAB-4, where the aquatics suddenly diminish (most clearly demonstrated by the *Pediastrum* curve) and the LOI-curve rises abruptly (Fig. 11). Here *Typha latifolia* reappears in the record indicating that summer temperatures have risen to ca. 14°C. The amelioration of the climate probably resulted in the degradation of (incipient) permafrost, a better infiltration of the precipitation into the groundwater system, a restorance of the seepage conditions near the site, diminished run-off and a decline in peakedness in the fluvial discharge. The bifurcation terrace was no longer inundated during periods of peak discharge. Locally, improvement of the drainage led to a rapid hydroseral succession. Only *Equisetum, Stratiotes aloides* and *Myriophyllum verticillatum* maintained. Both latter species are equiped to overcome freezing over of the shallow water surface: *Stratiotes* by sinking down in the sapropelium layer during the winter period and *Myriophyllum verticillatum* by producing vegetative reproductive organs in autumn. Moreover, *Myriophyllum verticillatum* is capable of thriving in a temporary emerging biotope, while *Stratiotes* does not root in the bottom sediments, but instead floats on the seasonally fluctuating water level. In the emerging border-zone of the lake *Populus tremula* spread (e.g. Van Geel et al. 1981) with an understory of ferns (*Thelypteris palustris*, Fig. 13).

Zone ZAB-5, 323-268 cm

Chronostratigraphy: this zone embraces the time interval between 10.4 ka and ca. 10.1 ka BP and may be correlated with the terminal phase of the Younger Dryas.

Lithology: peat changing into sandy peat between 308 and 275 cm with a sand maximum between 308 and 295 cm.

Populus tremula was succeeded by tree birch in the border zone of the channel. Subsequently, progressive degradation of the permafrost led to dry surface conditions, possibly enhanced by a decline in precipitation. A lowering of the phreatic level may explain the temporary decline in *Betula pubescens* in favour of *Pinus* at this level. This lowering in the water level and a concomitant spread in reedswamp vegetation has also been registered in lake Gosciaz at the Younger Dryas-Preboreal transition (Ralska-Jasiewiczowa et al. 1992). The small and shallow lake at Żabinko possibly is more sensitive to hydrological changes and thresholds in the system are reached earlier in the record. *Corylus*, in this interval, can no longer be interpreted as reworked and its occurrence is indicative for a further improvement of the climate. On the other hand dry surface conditions in the source area of the dunes, the braidplain to the west, triggered a phase with renewed aeolian activity (297-272 cm; LOI-curve and grainsize analyses, Fig. 11). Locally a *Thelypterido Phragmitetum intermingled* with *Filipendula, Typha angustifolia, Typha latifolia* and *Iris pseudacorus* established in the border zone of the channel. Likewise, in lake Łukcze (Bałaga 1990) *Typha latifolia* and *Nymphaea alba* reappear in the upper part of the Younger Dryas, indicative for a considerable amelioration of the summer temperature: ca. 14-15°C.

The reedswamp vegetation (*Phragmites* fruits are present in the macrobotanical record, Fig. 13) that was present in the upper part of the Younger Dryas, diminished when open water started to spread and was replaced by *Nymphaea alba, Sparganium* spp. and *Characeae*. The latter taxa is a pioneer on sandy lake-bottoms. The seepage zone moved away from the site. The increase in water depth may again be induced by the approaching parabolic dune and its updoming internal water table although its nearby presence was already established for the end of the Allerød. More likely is that precipitation started to increase. This should bring the aeolian activity to an end. Moreover, the spreading vegetation cover, under favourable climatic conditions has contributed to the fixation of the substratum.

Zone ZAB-6, 268-223 cm

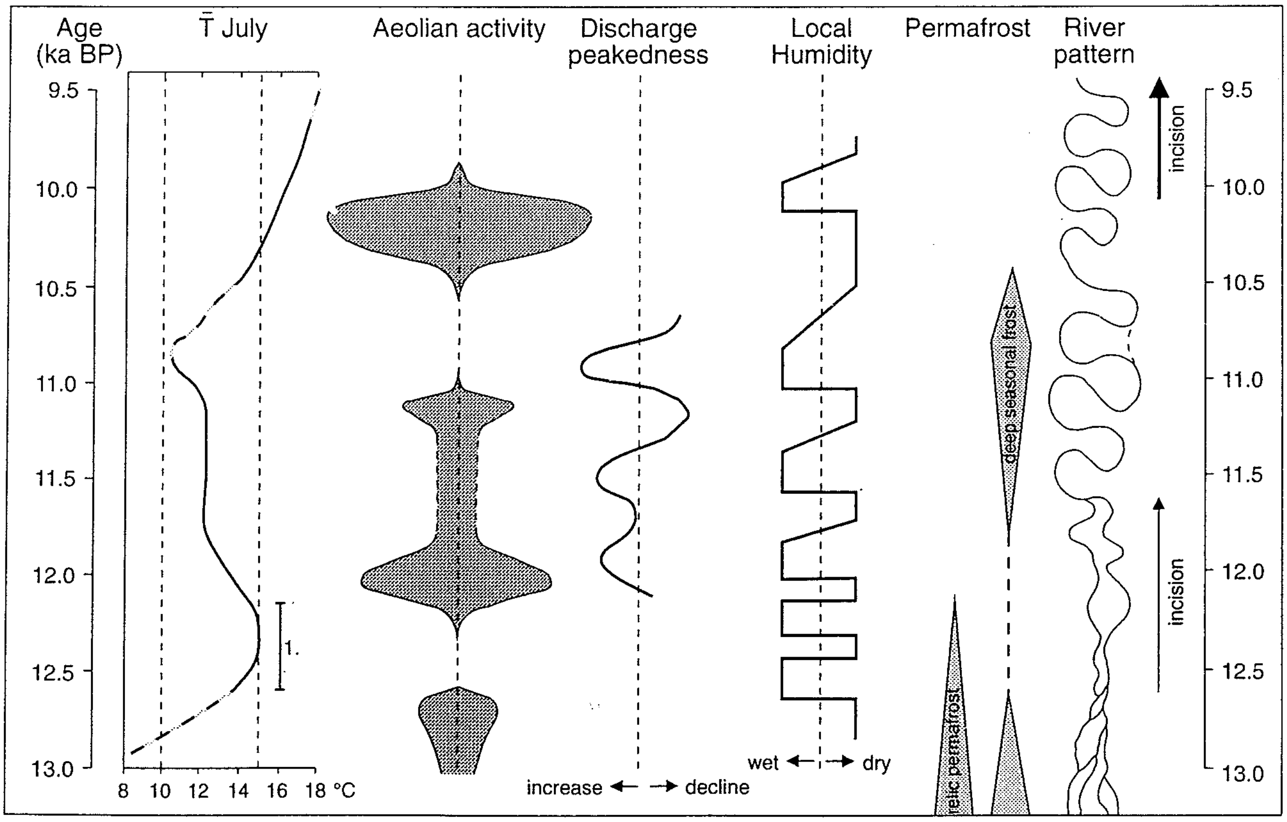
Chronostratigraphy: this zone embraces the time interval between ca. 10.1 ka and 9.8 ka BP and represents the early Holocene.

Lithology: peat.

Once the substratum became stabilized a further colonization of the area by *Pinus* is registered in the pollen record. The sandy dunes were pre-eminently the habitat for pine to spread and it rapidly outnumbered *Betula*. *Corylus* demonstrated a further increase while *Ulmus* was present in low frequencies. The appearance of *Ulmus* in the pollen assemblage of this zone is in agreement with the *Ulmus* iso-pollen maps (Ralska-Jasiewiczowa 1983), which demonstrate a rapid migration from southeastern Poland to the north and west. By 10 ka BP *Ulmus* reached the Great Polish Lowland of western Poland. Simultaneously with the increase in forest cover, effective precipitation and seepage to the depression diminished, leading to a subsequent hydroseral succession at the site as is demonstrated by the increase in *Typha latifolia* and *Thelypteris palustris* in the upper samples. Again *Populus tremula* responded by spreading on the emerging border zone of the channel. The upper spectra may be correlated with the Rammelbeek-phase (Van Geel et al. 1981) which is dated at ca. 9.8 ka BP.

Interactions between climate, vegetation, fluvial adjustment and aeolian activity during the Vistulian Lateglacial (Fig. 14)

The stacked series of sediments in the bottom of the sand pit at Żabinko (unit I and II) demonstrates the presence of a braided system on the bifurcation terrace. This drainage system was active during the disintegration of the land-ice cover in the Vistulian Late Pleniglacial up to its abandonment at ca. 12.6 ka BP. During the terminal phase of the braided system (unit II) aeolian processes became active on the



1. based on insect assemblages

Fig. 14. Summary of the Vistulian Lateglacial climatological and environmental changes in the Warta valley near Żabinko

braidplain in the absence of a closed vegetation cover. Following the increase in mean July temperature from ca. 12.6 ka (up to 14 to 15°C), a spreading vegetation cover in which *Betula* and *Hipphophae* formed major constituents, gradually stabilized the substratum. The spreading vegetation cover forced the fluvial system to organize its drainage system. Transitions to a meandering incising system occurred. Aeolian activity was hampered and soil formation prevailed (unit III).

This phase of stability was interrupted at ca. 12.1 ka BP when aeolian activity on the bifurcation terrace had resumed. This was induced by a degradation in the vegetation cover, which in return may be explained by a drying up of the upper soil layer due to a lowering of the groundwater level. As there are no indications for a climatic deterioration during that period, it is assumed that the drier conditions in the top sediments are of geomorphological or hydrological origin. Particularly, lowering of the groundwater level can be triggered by two processes: 1) the climatic upwarming that started at ca. 12.6 ka BP ultimately, with some time lag, resulted in the disintegration of the permafrost (Kozarski 1991) and in an increased infiltration capacity, 2) the vertical erosion that took place after the river abandoned the former braidplain (the bifurcation terrace) may have led to a lowering of the groundwater level on the adjacent terrace. This process was invoked previously to explain dry conditions during the Older Dryas in the valley bottoms in the Netherlands (Vandenberghe et al. 1987).

Apparently, abandoned transitional channels on the bifurcation terrace were still flooded during periods of peak discharges in the then active meandering system. Under a prevailing WNW wind direction the inland dunes gradually migrated over the bifurcation terrace and its abandoned channels of the transitional system. From ca. 12.2 ka BP the migrating dunes dammed the drainage through the branch of the transitional system at Żabinko and diverted its course in a NNE direction along the dune front. Standing water remained in the palaeochannel after flooding events. The pollen assemblage of the basal part of the infill can be assigned to the terminal phase of the Bølling (ZAB-1) and Older Dryas (ZAB-2) period and mean July temperatures were around 14°C. The floodplain during this period became colonized by a heliophilous shrub vegetation consisting of small birches, *Juniperus* and *Populus*. *Pinus* found its habitat on the more elevated positions (the dunes) in the floodplain.

Towards the end of the Older Dryas, ca. 12 ka BP, the inundation frequency declined and a succession towards a birch-pine forest took place. The heliophilous shrub vegetation gradually became shaded out and aeolian activity was probably reduced due to fixation of the substratum.

In the basal part of the succeeding period, the Allerød, a decline in the summer temperature is registered from ca. 14 to ca. 12°C. The cooling trend provoked seasonal frost, the breaking up of soils and increased peakedness in river discharge. Simultaneously the aeolian activity seemed to be reactivated, which resulted in a distinct aeolian influx in the palaeochannel at Żabinko towards the end of the Allerød.

Intensified seasonal frost or incipient permafrost is the most likely process that triggered the environmental changes at the Allerød/Younger Dryas transition (ca. 11 ka BP). Infiltration of the precipitation into the groundwater system is greatly hampered due to (long lasting) ground ice. A concomitant increase in soil moisture reduced the supply of sand in the source area of the dunes. Increased run-off and possible snow-melt in spring or early summer, contributed to increased peakedness in the fluvial system. The palaeochannel at Żabinko was again reached during periods of peak discharge and the coarse sand fraction in the infill at this level indicates the highest stream velocities since its abondonment.

Subsequently, towards 10.4 ka BP, inundation frequencies diminished and locally a hydroseral succession led to a transition from gyttja to peat. A climatologically dry period with reduced precipitation and diminished fluvial discharge may be concluded. At ca. 10.4 ka BP summer temperatures had risen to ca. 14°C and dry conditions were enhanced by the desintegration of residual ice-lenses. Aeolian activity was reactivated and a distinct aeolian phase is registered in the infill of the palaeochannel.

By the start of the early Holocene effective precipitation increased leading again to a rise in the phreatic level and open water conditions in the palaeochannel at Żabinko. This event effectively brought the Vistulian Lateglacial aeolian activity on the bifurcation terrace to an end.

Acknowledgements

We would like to express our gratitude to the crew of the laboratory for sediment analyses of the Faculty of Earth Sciences; to Wim Hoek and Gerard Aalbersberg for their assistence during computer processing of the data; to Gijs Hillenius for his dedicated pollen analytical work and to Prof K.E. Behre, who critically read the manuscript.

References

Ahlbrandt, T.S., Fryberger, S.G., 1982: Introduction to eolian deposits. 11-47. In: Scholle, P.A., Spearing, D. (eds.): Sandstone Depositional Environments. Am. Ass. Petroleum Geol., Tulsa, Oklahoma, U.S.A., 410 pp.

Bałaga, K., 1990: The development of lake Łukcze and changes in the plant cover of the south-western part of the Łęczna-Włodawa lake district in the last 13 000 years. *Acta Palaeobot.* 30, 77-146

Bińka, K., Cieśla, A., Łacka, B., Maeyska, T., Szeroczyńska K., Więckowski, K., 1991: The development of Błędowo lake (Central Poland) – A palaeoecological study. *Studia Geol. Polonica* 100, 1-87

Eicher, U., 1979: Die $^{18}O/^{16}O$ und $^{13}C/^{12}C$-Isotopenverhältnisse in spätglacialen Süsswasserkarbonaten und ihr Zusammenhang mit den Ergebnissen der Pollenanalyse. Dissertation Universität Bern, 205 pp.

Faegri, K., Iversen, J., 1975: Textbook of Pollen Analysis. Munksgaard, Köbenhavn, 295 pp.

FAO 1988 FAO/Unesco soil map of the world, revised legend. *World resoursces report* 60, FAO, Rome. Reprinted as technical paper 20, ISRIC, Wageningen, 1989

Gonera, P., Kozarski, S., 1987: River channel changes and rough paleodischarge estimates for the Warta river, West-Central Poland. *Geografiska Annaler* 69A, 163-171

Iversen, J., 1954: The Late-Glacial flora of Denmark and its relation to climate and soil. *Danm. Geol. Unders.* IIRk 80, 87-119

Kasse, C., Vandenberghe, J., Bohncke, S., 1994: Climatic change and fluvial development of the Maas during the late Weichselian and early Holocene. *Paläoklimaforschung/Palaeoclimate Research* 14 (special issue 9; in press)

Kolstrup, E., 1980: Climate and stratigraphy in Northwestern Europe between 30,000 B.P. and 13,000 B.P., with special reference to The Netherlands. *Meded. Rijks Geol. Dienst* 32, 181-253

Kozarski, S., 1983: River channel changes in the middle reach of the Warta valley, Great Poland Lowland. *Quat. Stud. Poland* 4, 159-169

Kozarski, S., 1991: Warta – A case study of a lowland river. 189-215. In: Starkel, L., Gregory, K.J., Thornes, J.B. (eds.): Temperate palaeohydrology. Wiley and Sons, Chichester, 548 pp

Kozarski, S., Rotnicki, K., 1977: Valley floors and changes of river channel pattern in the North Polish Plain during the Late-Würm and Holocene. *Quaestiones Geographicae* 4, 51-93

Kozarski, S., Tobolski, K. (eds.) 1981: Guide-book of excursions, Symposium "Paleohydrology of the temperate zone" (Poznań, Poland '81, September 22-28). INQUA Eurosiberian subcommission for the study of the Holocene IGCP No. 158, Adam Mickiewicz University, Poznań, 3-73

Kozarski, S., Gonera, P., Antczak, B., 1988: Valley floor development and paleohydrological changes: The Late Vistulian and Holocene History of the Warta River (Poland). 185-203. In: Lang, G., Schlüchter, C. (eds.): Lake, Mire and River Environments During the last 15 000 years. Balkema, Rotterdam, 229 pp.

Kozarski, S., Nowaczyk, B., 1991: The Late Quaternary climate and human impact on aeolian processes in Poland. Z. *Geomorph.* N.F., Suppl.-Bd. 83, 29-37

Lemdahl, G., 1991: Late Vistulian insect assemblages from Żabinko, Western Poland. *Boreas* 20, 71-77

Manikowska, B., 1977: The development of the soil cover in the Late Pleistocene and the Holocene in the light of fossil soils from dunes in Central Poland. *Quaestiones Geographicae* 4, 109-129

Manikowska, B., 1985: On the fossil soils, stratigraphy and lithology of the dunes in Central Poland. *Acta Geographica Lodziensia*, 52, 137 pp.

Miall, A.D., 1978: Lithofacies types and vertical profile models in braided rivers: a summary. In: Miall, A.D. (ed.): Fluvial sedimentology. *Can. Soc. Petrol. Geol. Mem.* 5, 597-604

Müller, H., 1953: Zur spät- und nacheiszeitlichen Vegetationsgeschichte des mitteldeutschen Trockengebietes. *Nova Acta Leopoldina* 16-110, 1-67

Nowaczyk, B., 1986: The age of dunes, their textural and structural properties against atmospheric circulation pattern of Poland during the Late Vistulian and Holocene. *Seria Geografia* 28, Adam Mickiewicz University Press, Poznań, 245 pp.

Ralska-Jasiewiczowa, M., 1983: Isopollen maps for Poland: 0-11,000 years BP. *New Phytologist* 94, 133-179

Ralska-Jasiewiczowa, M., Van Geel, B., Goslar, T., Kuc, T., 1992: The record of the Late Glacial/Holocene transition in the varved sediments of Lake Gosciaz, Central Poland. *Sveriges Geologiska Undersökning* 81, 257-268

Schwan, J., 1988: Sedimentology of coversands in Northwestern Europe. Thesis Vrije Universiteit, Elinkwijk, Utrecht, 137 pp.

Siegenthaler, U., Eicher, U., Oeschger, H., 1984: Lake sediments as a continental ^{18}O records from the Glacial/Post-Glacial transition. *Ann. of Glaciology* 5, 149-152

Stockmarr, J., 1971: Tablets with spores used in absolute pollenanalysis. *Pollen et Spores* 13, 615-621

Tobolski, K., 1981: Results of paleobotanical investigations of deposits filling the paleomeander at Jaszkowo. In: Kozarski, S., Tobolski, K. (eds.) Guide-book of excursions, Symposium "Paleohydrology of the temperate zone" (Poznań, Poland '81, September 22-28). INQUA Eurosiberian subcommission for the study of the Holocene IGCP No. 158, Adam Mickiewicz University, Poznań, 31-35

Tobolski, K., 1988: Palaeobotanical study of Bølling sediments at Żabinko in the vicinity of Poznań, Poland. *Quaestiones Geographicae* 10, 119-124

USDA 1983: Keys to soil taxonomy. *Soil Management Support Services, Technical Monograph* 6

Vandenberghe, J., 1994: Postglacial river activity and climate: state-of-the-art and future prospects. *Paläoklimaforschung/Palaeoclimate Research* 14 (special issue 9; in press)

Vandenberghe, J., Bohncke, S., Lammers, W., Zilverberg, L., 1987: Geomorphology and palaeoecology of the Mark valley (southern Netherlands): geomorphological valley development during the Weichselian and Holocene. *Boreas* 16, 55-67

Vandenberghe, J., Kasse, C., Bohncke, S., Kozarski, S., 1994: Climate-related river activity at the Weichselian – Holocene transition: a comparative study of the Warta and Maas rivers. *Terra Nova* 6, 476-585

Van Geel, B., Bohncke, S., Dee, H., 1981: A palaeoecological study of an upper Late Glacial and Holocene sequence from 'De Borchert', The Netherlands. *Rev. Palaeobot. Palynol.* 31, 359-448

Zagwijn, W.H., 1984: The formation of the Younger Dunes on the west coast of The Netherlands (AD 1000-1600). *Geol. Mijnbouw* 63, 259-268